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Electrical REVIEW

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THE COVER

DWARFED by the processing units they serve, these 5000/6250 kv; 13,800—2400V and 750/862 kva, 13,800—480V transformers supply power to one of thirteen major switch houses at Tidewater Oil Company's new Delaware Flying A Refinery 15 miles south of Wilmington, Delaware. The story of this outstanding refinery begins on page 4.

Allis-Chalmers staff photo by Frank Hart

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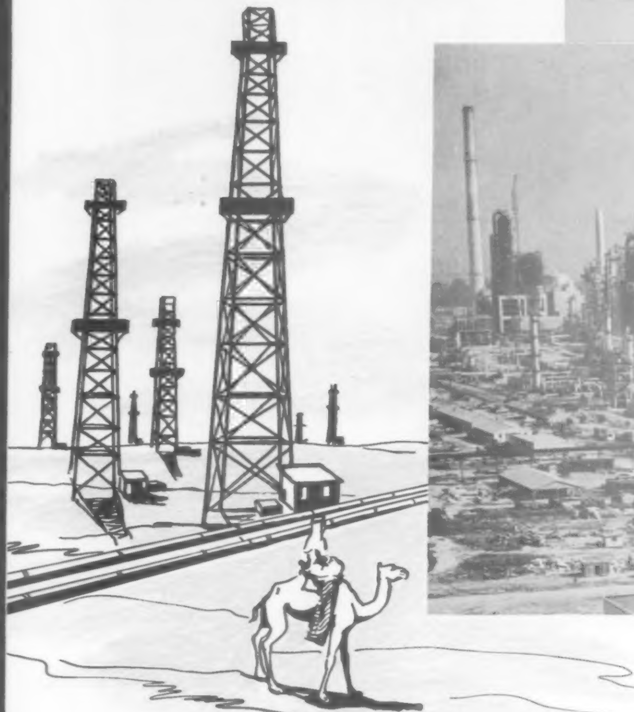
TIDEWATER'S FLYING A REFINERY



NEARING COMPLETION, parts of Tidewater's new Delaware Flying A Refinery are already in operation. This view looks toward the powerhouse stack nearly a mile away from the site near the administration building where this photo was taken. All of the main process units are built along the "main street" of the refinery defined by the elevated assembly of piping behind the units. **(FIGURE 1)**

Here and in the following two articles is the story of the largest refinery ever built at one time — anywhere.

IN AN INDUSTRY where new records are an everyday occurrence, pioneering is standard procedure, and bigness commonplace, a new facility has been "rising" that makes engineers everywhere pause for a long, second look.

"Rising" is perhaps the best way of describing the building of the Tidewater Oil Company's new Delaware Flying A Refinery near Delaware City, on the west bank of the Delaware River 15 miles south of Wilmington. The powerhouse stack reaches 500 ft into the sky, and many of the towers and processing units are among the tallest in existence — 200 ft and higher.

The story behind this new industrial giant is an interesting study of top-notch planning, designing and construction in the petroleum processing industry. The refinery will cost well over $100,000,000 and is designed to produce about one-tenth of all the gasoline, fuel oil and other petroleum products used in the Middle Atlantic States.

The facility will handle an initial capacity of 130,000 barrels of crude per day. No one ever before built that much new capacity in one refinery at one time. Only a handful of refineries in the entire world are larger and those were built up over a period of many years. The capacity is almost one-third of all the new refining facilities added in the oil-hungry U.S. during 1956 and nearly 1½ percent of the nation's total capacity for refining crude oil. In some of the higher grade petroleum products, the plant will produce a far greater share of the total U.S. capacity.

It takes study, confidence, and lots of courage to even begin planning a plant the size of the Delaware Flying A Refinery. But in 1953, when Tidewater was faced with the decision of modernizing its out-of-date Bayonne, New Jersey, refinery, or of building a completely new unit, the decision was clear cut. Arrangements were made to close down and sell the Bayonne plant while initial work on a new refinery went ahead.

Consulting engineers handle both planning and construction

Early in the company's planning, consulting engineering firms were brought into the picture. After a study of preliminary proposals, C. F. Braun & Co., of Alhambra, Calif., were chosen to design and construct the entire plant

Tidewater Oil Company Began As Pioneering Venture

Paradoxically, the Delaware Flying A Refinery, which is not connected to any oil pipeline, is owned by the company whose predecessors built the first long-distance crude oil pipeline from Titusville, Pa., to the Atlantic Seaboard. Thus came the name of the pioneer company, the Tide-Water Pipe Company, Ltd.

Today the Tidewater Oil Co. — with headquarters at San Francisco — is one of the nation's major oil producing and distributing organizations. They are active in all phases of the petroleum business — from well to consumer — marketing the well-known Flying A gasolines and Veedol motor oils throughout the 48 states, Hawaii, and the Philippine Islands and more than 70 countries of the Free World. When the Delaware Flying A Refinery goes into service early in 1957, the company's refining capacity will total 245,000 barrels a day.

on a "turnkey" contract, with partial operation to begin within eighteen months.

The stipulations laid down by Tidewater engineers were simple. The plant was to be the most efficient and economical plant that could be designed with safety, economy, and flexibility uppermost in mind. Furthermore, the decisions in choice of equipment, layout, and procedures were to be in the hands of the consulting engineers with almost no "strings" attached. Refinery engineers were, of course, to be consulted on all major decisions. That this policy was followed was attested by the fact that subsequent departures from the consultants' recommendations were seldom made and then only for important reasons.

As soon as contract arrangements were concluded, C. F. Braun & Co. set up a project supervisory group staffed from all divisions of the company. This project was divided into two main classifications. One covered the engineering and construction of the General Facilities and the other the Process Units.

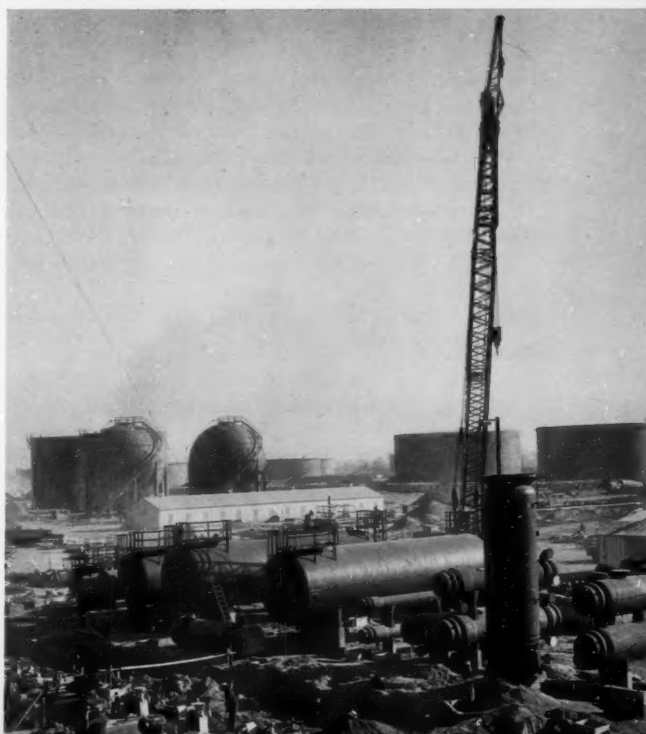
Under General Facilities, there was a further division into seven units, including Site Grading and Roads, Water Terminal, Water Pumping Plant, Water Treatment Plant, Tank Farms, Electrical Power Distribution System, and Refinery Buildings.

There were eleven Process Unit subdivisions: Crude Unit, Fluid Coker, Fluid "Cat," Cracker and Fractionator, Gas Plant, Catalytic Reformer, Polymerization Plant, Alkylation Plant, Sulphur Recovery Plant, Catalytic Desulphurizer, Hydrogen Unit, and Udex Extraction Unit. In addition Braun & Co. received a contract to build the complete power plant at the refinery site for the Delaware Power and Light Co.

One section of the Braun Electrical Department was set up to work entirely on the power plant and another on the refinery distribution system including substations, motor control, motors, communications, and lighting. This latter section was further divided into several smaller groups of five or six engineers under group leaders. Each of these groups was assigned the task of engineering all of the electrical equipment for three or four of the General Facilities or Process Units.

C. F. Braun & Co.
Consulting Engineers to the World

Forty-seven years ago, Carl F. Braun, a young mechanical engineer, entered the profession as a consulting engineer after graduation from Stanford University. Today, the name of C. F. Braun & Co. is synonymous with outstanding engineering and construction projects everywhere in the free world. The Company is best known for its ability to deliver complete industrial projects ready to go on a "turnkey" basis — chemical plants, metal refining facilities, steam generating plants and, of course, oil refineries. The Flying A Refinery has been one of the larger projects handled by the Company to date. The organization has one of the largest heavy duty fabricating shops in the country, owns millions of dollars worth of major construction tools and equipment, and maintains one of the most efficient engineering organizations in existence.



MOTORS, PUMPS, VESSELS, and heat exchangers in seeming disorder mark the beginning of the refinery's gas plant facilities. In the background are some of the tanks in the 7,000,000 barrel capacity tank farm. **(FIGURE 2)**

TWO HUNDRED MILES of underground electrical lines are required to furnish the backbone of electrical power distribution at the Flying A Refinery. This huge ditch was an early step in construction, as it carries part of the 48 miles of concrete ducts used for power distribution. (FIGURE 3)

Largest industrial site on Atlantic Seaboard

The site that had been selected was a 5000 acre group of tracts made up largely of farms. Only about one-tenth of the land was to be used initially, the rest was to remain as farm land on a lease basis. The site was rolling, averaging about 60 feet above sea level and the Delaware River.

The area was one that favored additional refinery expansion. It is on the fringe of the Philadelphia metropolitan district. The market within a practical shipping distance consumes about one-fourth of all the fuel and gasoline in the U.S., yet it contains a much smaller proportion of the nation's refining capacity. Furthermore, excellent shipping facilities, both rail and water, were readily available and there was an ample supply of water readily available for cooling. (A plant like the Delaware Flying A Refinery and its supporting power plant uses 60 gallons of water for every gallon of crude processed.)

A few details on the individual units at the site will be of interest. The crude unit, largest in the world, will take the entire volume of all incoming oil, converting the lighter fraction into gas, gasoline, and naphtha, with the bulk of the liquid going on to further refining. The Orthoflow fluid catalytic cracker is likewise the largest such unit ever built and has a rated capacity of 102,000 barrels a day. It handles the heavier fraction remaining after the initial crude unit processing.

Utility sells kwhr; refinery, coke

The fluid coking process is one of the most important developments in recent years in the refining field, solves a long standing disposal problem for the industry and provides an economical source of fuel for efficient burning in power plant boilers. The 42,000-barrel-per-day fluid coker at Tidewater's new plant is one of the few such units ever built and is far larger than those now installed. The coker works on the heavy asphalt-like fractions remaining after the crude has gone through all the refining processes. Under controlled conditions of temperature and pressure, the heavy crude is vaporized, then condensed on minute particles of coke. The oil evaporates, leaving a dry, black, finely-powdered fuel, clean enough to rub in your hand, yet containing 14,000 Btu's per pound, nearly twice as much as the lighter gasoline fractions. Besides producing fluidized coke, the process also recovers some additional fuel oil fractions. The amount of this recovery can be varied as demand for heavy fuels warrants.

The fluid coke is piped by compressed air to storage silos prior to burning in the specially designed 500,000 lb/hr boilers at the power plant. The boilers will also operate efficiently on gas and heavy fuel oil.

The power plant, owned and operated by the Delaware Power and Light Company, is being operated under a type of contract growing in favor among refineries and the utility industry in recent years. Essentially, the plan works like this. The Delaware Power and Light Co., the utility serving the area, provides all of the process-steam and electrical energy needed by the refinery. The plant is incorporated as one more generating facility on the D. P. & L. Co. system. The utility is furnished coke (and gas) from the refinery. The refinery, in turn, is furnished steam and kilowatt-hours which may come from the power plant or from the utility's tie line. There are many obvious advantages to both industries under such an arrangement.

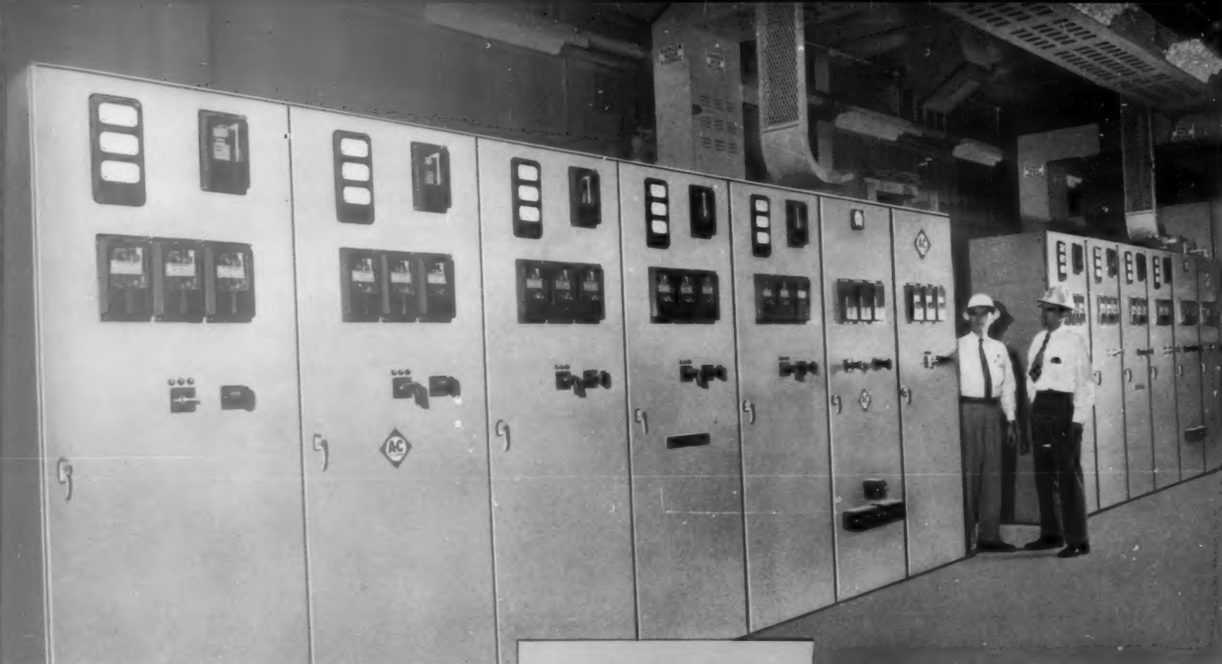
Careful planning — secret of erection on schedule

Erecting a refinery like the Flying A in less than two years involves an almost unbelievable amount of planning. Equipment had to be on hand when and where it was needed, but not so much ahead of time that valuable electrical or precision equipment would be damaged by adverse weather. (Some of the substation equipment was kept in newly built oil storage tanks as a protection against moisture.) Throughout most of 1955 and 1956, upwards of 9,000 men were working at the site and nearly a hundred carloads of equipment were unloaded daily, with truckloads of supplies arriving every few minutes.

By the time the job is finished nothing but men's memories and photographs will remain to show the tempo of activity that built one of the oil industry's great accomplishments and its most modern refinery.

* * *

EDITOR'S NOTE: The REVIEW is grateful to the engineers of Tidewater Oil Co. and C. F. Braun & Co. and to Frank Nolan of the Allis-Chalmers Switchgear Dept. for their help in the preparation of this series of articles.



TYPICAL OF THE MANY SWITCHGEAR assemblies throughout the refinery is this group in the main power plant. Equipment had not yet been energized when photo was taken just after installation. **(FIGURE 4)**

Power Distribution AT TIDEWATER'S FLYING A REFINERY

by **C. W. BOICE**
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Electrical Engineering Dept.
C. F. Braun & Co.
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S. R. DURAND
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The Flying A Refinery will need 40,000 kw for initial operation — more later. Here is how the ultra reliable distribution system was designed.

THE TIDEWATER Oil Company's Delaware Refinery will require about 40,000 kw of power for initial operation. The final scheme for distribution of this power divides the load among six 13.8 kv switchgear buses leaving the power plant. Each bus has a main 1200 ampere air circuit breaker and four or five feeder breakers. There are a total of twenty-seven underground 13.8 kv cable feeders to the substations in the refinery and one overhead 13.8 kv line to the water terminal. Figure 5 shows a simplified master diagram of the refinery power system.

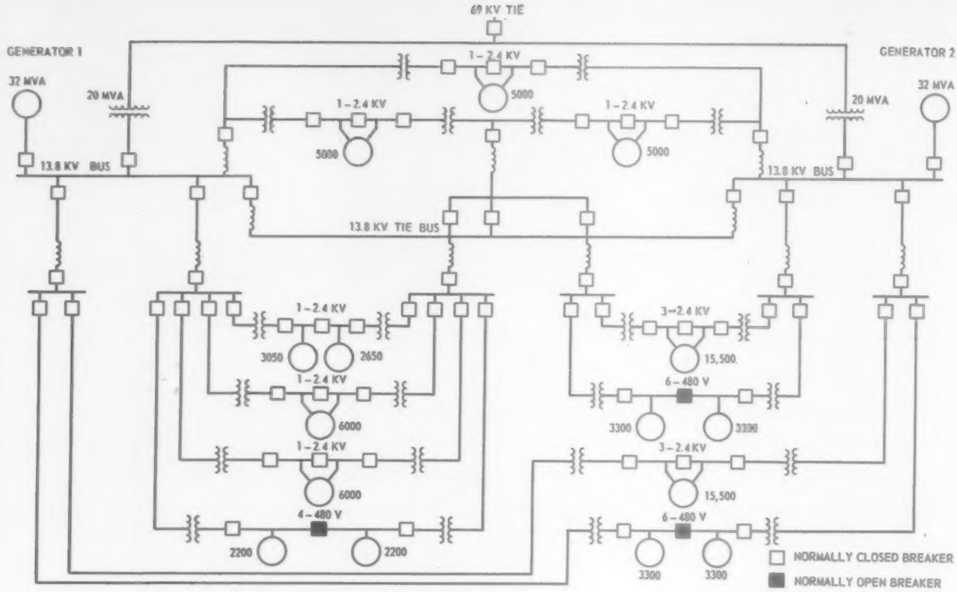
About two-thirds of the power will be distributed through spot network substations rated 13,800 volts to 2400 volts to supply the 2300 volt motors in the refinery. There are nine of these spot network substations, each having two 5000/6250 kva transformers.

The other one-third of power is distributed to fourteen 13,800 to 480 volt secondary selective load center substations, each having two 750/862 kva transformers. There are also two radial type 750 kva substations, and a number of 300 kva and smaller transformers for supplying some isolated outdoor 440 volt motor control and switch racks.

There are about two dozen assemblies of 2300 volt motor control with air contactors, both fused and nonfused types. Over one hundred of these motor contactors are installed. There also are about sixty 440 volt motor control centers distributed throughout the refinery for small motors, portable equipment, etc.

In comparison with outdoor switchgear it was found to be more economical to install indoor switchgear and build switch houses which could house instrumentation and control as well as provide shelter for maintenance and operating personnel throughout the huge plant. There are fourteen switch houses, most of them containing both 2400 volt and 480 volt substations plus several 2300 and 440 volt motor control assemblies. The transformers are installed outdoors and are connected to the indoor switchgear by bus ducts. Due to hazardous vapor conditions that can exist in some areas of refineries, a vapor seal is built into all bus ducts entering the switch houses.

The houses are pressurized with air drawn into them through a duct extending above the roof where there is less likelihood of explosive vapors existing. Cable vault entrances are gasketed and cable ducts are held at a pressure



SIMPLIFIED MASTER DIA of the refinery shows how the key 2400-volt substatio modified spot network wi mally closed breakers. Sub shown above the 13.8 kv are located at the power Total horsepower of motors type are lumped as one each substation to simplify lation. **(FIGURE 5)**

higher than the switch houses. All of the petroleum lines in the refining area are overhead, so there is no hazard from underground leaks.

All transformers are oil-insulated and of sealed-tank construction with welded-on tubular radiators. They are equipped with high voltage disconnecting switches capable of breaking magnetizing current.

Every precaution was taken to reduce explosion hazards to a minimum. Cooling fan motors are of explosion-proof design with top oil thermometer control. The test switch for the fans on each transformer is also of the explosion-proof type. All transformers have sudden pressure relays with conduit wiring to and from the explosion-proof terminal box sealed in compound-filled sealing condulets.

Spot network substations for 2400 volt power

The 5000 kva transformers for the spot network substations have a forced air fan-cooled rating of 6250 kva. Normally, in a spot network substation, each transformer has sufficient capacity to carry the entire load in case the power supply to the other transformer is interrupted. Experience indicates that the greatest likelihood of trouble will be from cable failures in the 13.8 kv underground cable distribution system to the substations. Cables from different switchgear buses are run through separate duct lines to each transformer in order to localize the loss of power at one end of a substation. As a consequence, if power is lost to one transformer, the other transformer with fan-cooling has sufficient capacity to maintain the en-

CALCULATING BOARD STUDY ASSURES SYSTEM STABILITY

AN INTERESTING SIDELIGHT in the design of the refinery was the study[1] made on the A-C network calculating board at Illinois Institute of Technology in Chicago. The primary purpose of this study was to discover if all motors in the refinery could reaccelerate their loads after a severe fault in the system.

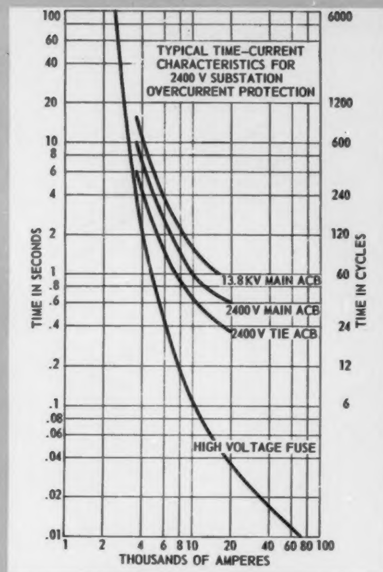
Almost every high voltage motor starter in the refinery is equipped with a timing device, which after a power outage will reclose the starter if power was restored within four seconds' time. Thus, after a severe fault or dip in system voltage, during which motor starters drop out, a large number of motors will have to be reaccelerated as soon as voltage recovers. Figure 8 shows a portion of the simplified master diagram (Figure 5). A solid three-phase fault at point "X" at one end of the 13.8 kv distribution bus was considered to be the worst possible fault that might occur.

It would have required thousands of man-hours to calculate the transient response of the generators and motors at each combination of voltage and phase angle conditions that could exist throughout the system during recovery after such a fault. However, by setting up the system on the calculating board with simulated generators, transformers and motor characteristics and then applying a fault, data could be obtained enabling designers to determine critical points through a reasonable number of step-by-step calculations. Figure 2 shows a typical circuit of the equivalent motor load.

The first calculating board study established requirements for special motor characteristics for the large slow speed compressor motors. These were to provide 105 percent full load torque at 80 percent of normal speed and 75 percent of normal voltage.

It was also discovered that if the 2300 volt air-break motor starters could be modified to remain closed unless the voltage dipped to less than 35 percent of normal (and then to drop out only after a nineteen cycle time delay),

PICAL SWITCH HOUSE LAYOUT of switchgear, high voltage motor control, and low voltage motor trol. Assembly at left has 2400 volt switchgear centered between four 2300 volt motor controls at each . The 440 volt control assembly at right includes metering panels, 25,000 and 50,000 ampere breakers numerous spare compartments for future electrical expansion. **(FIGURE 6)**



RELAY TRIPPING CURVES show how time delay settings assure tripping of only the proper breaker. **(FIGURE 7)**

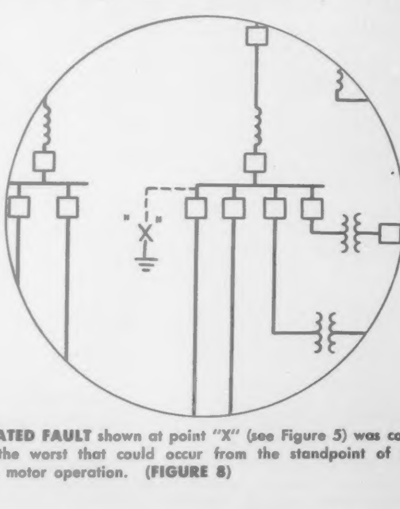
tire load for an hour or more. Within this time, it is expected that an operator will be able to reduce the load within the transformer continuous fan-cooled rating.

The spot network substations at the Delaware Flying A Refinery were modified by including a normally-closed tie breaker in the 2400 volt bus. This tie breaker is opened and locked out only in case of a bus fault on either side of the 2400 volt bus. It is very unlikely that a bus fault on the 2400 volt switchgear or 2300 volt motor control buses connected to it will occur, but here, too, provision is made to maintain production because most motors essential to a process operation will have a spare non-operating motor connected to the other side of the bus. Thus, an operator can immediately start up the spare motors and maintain service from one transformer feeding one-half the bus. In most places in the system this switch-over is performed automatically.

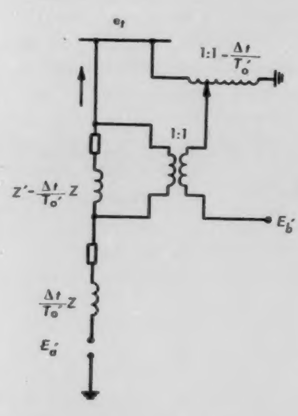
In many refineries built up to this time, practically all pumps and compressors in use during emergencies are driven by mechanical drive turbine units. This necessitates maintaining a very large supply of steam throughout the entire refinery for emergency use only. For the first time in such a large refinery, emergency steam drives have been kept to a minimum because of the high degree of relia-

the motors would remain connected to the system and would be in very little danger of damage.

Because no refinery had ever been designed so extensively with a power and distribution system intended to "ride through" severe system faults, a second study several weeks later, using all of the final circuit and component



SIMULATED FAULT shown at point "X" (see Figure 5) was considered to be the worst that could occur from the standpoint of affecting refinery motor operation. **(FIGURE 8)**



$$e_b' = e_t\left(1 - \frac{\Delta t}{T_o'}\right) + i\left(Z' - \frac{\Delta t}{T_o'} Z\right)$$

$Z = r_s + jx$

$Z' = r_s + jx'$

$X = X_s + X_m$

$X' = X_s + \frac{X_r X_m}{X_r + X_m}$

X_s = STAT. LEAKG. REACT.

X_r = ROT. LEAKG. REACT.

X_m = MAGNETIZING BRANCH REACT.

r_s = IND. MACHINE A–C STATOR RESIST.

Δt = TIME INTERVAL, SEC.

i = STATOR CURRENT

T_o' = OPEN CIRCUIT TIME CONSTANT, SECOND

E_a' = INT. VOLT. START INTVL.

E_b' = INT. VOLT. END INTVL.

e_t = TERMINAL VOLTAGE

EQUIVALENT CIRCUIT (above) for induction motors is shown as used for calculating board studies. **(FIG. 9)**

MORE ON CALCULATING BOARD STUDY (OVER)

NETWORK ANALYZER STUDIES took only a few days once the initial planning had been done. The effect of a short circuit and the resultant instability throughout the simulated system were studied for each .02 second interval following the fault. (FIGURE 10)

bility expected from the spot network substation power distribution system. Turbine drives are used for those spare pumps and compressors that must be kept operating after an emergency to insure safe shutdown. In a few places in the refinery this principle calls for electrical non-operating spares as standbys in case of steam supply failure.

An important advantage of modified spot network substations with normally-closed tie breakers (as contrasted with secondary selective substations with normally-open tie breakers) is that automatic bus transfer is eliminated. After a loss of voltage on a bus, a residual voltage produced by the motors may persist for a second or more until it decays. If power must be transferred between buses within this time, there is always the danger that the motor supply cables will be re-energized with power as much as 180 degrees out of phase with the residual voltage of the motors. This may cause greater mechanical stress within the motors than they can withstand. Eventual damage such as loosening of windings or end turn bracing can occur. Spot network substations overcome this.

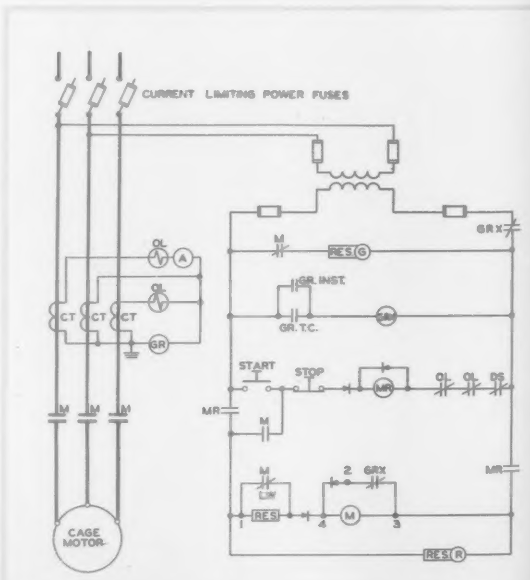
Another advantage of spot network substations is that the motor load is normally supplied from two power station switchgear buses through two transformers. In starting and simultaneously accelerating several large motors, the voltage of the system is affected less than if these motors were connected to one transformer only.

In line with good planning for future growth, all of the substations throughout the Tidewater plant are provided with ample space for the additional feeders that will be needed as the refinery grows in the years ahead.

values, offered several advantages. Designs for the power plant and utility interconnection were firmly established, and voltage conditions during system faults could be predicted with greater accuracy. Characteristics of the motors and control, as modified, were available at accuracies sufficient to predict exact response. The second study showed the transient response of the entire system would meet all expectations, confirming the advantages of modifying motor and contactor designs for this unusual distribution system.

Subsequently, a further improvement was made in the contactor control circuit as shown in Figure 11. This consisted in connecting the ground fault lockout relay of each contactor so that the paralleled branch of the rectifier circuit across the contactor coil was opened if a ground fault occurred in any motor or motor cable circuit. Thus, when necessary, the contactor can drop out within three or four cycles instead of about nineteen cycles and high speed ground fault protection is achieved. Since almost all cable faults will be phase-to-ground, faster opening time for the contactors is a definite advantage.

[1] "A Transient Stability and Voltage Study for a Modern Oil Refinery Distribution System," by C. W. Boice, S. R. Durand, D. Dalasta, AIEE CP 56-767.



UNUSUAL MOTOR STARTER control circuit allows solenoid current to decay slowly, enabling motor to remain connected to line for the optimum interval during a system disturbance. (FIGURE 11)

THE STORY OF SWITCH HOUSE 31

ONE WAY to appreciate the size of the Tidewater Oil Company's new Delaware Flying A Refinery and the job of designing it is to take a close look at one of the thirteen substation centers called "switch houses." Switch House 31, typical in many ways, is located on the eastern edge of the refining unit plot about one-third of the way from the administration building to the powerhouse.

This particular switch house serves both the Unifiner and the Hydrogen units. This was done because the two processes are in close proximity and secondary cables could be held to a reasonable length. Total load from both units was within the rated capacity of two 2400 volt, 5000/6250 kva transformers and one 480 volt, 750/862 kva transformer, the ratings which had been selected as standard throughout the refinery.

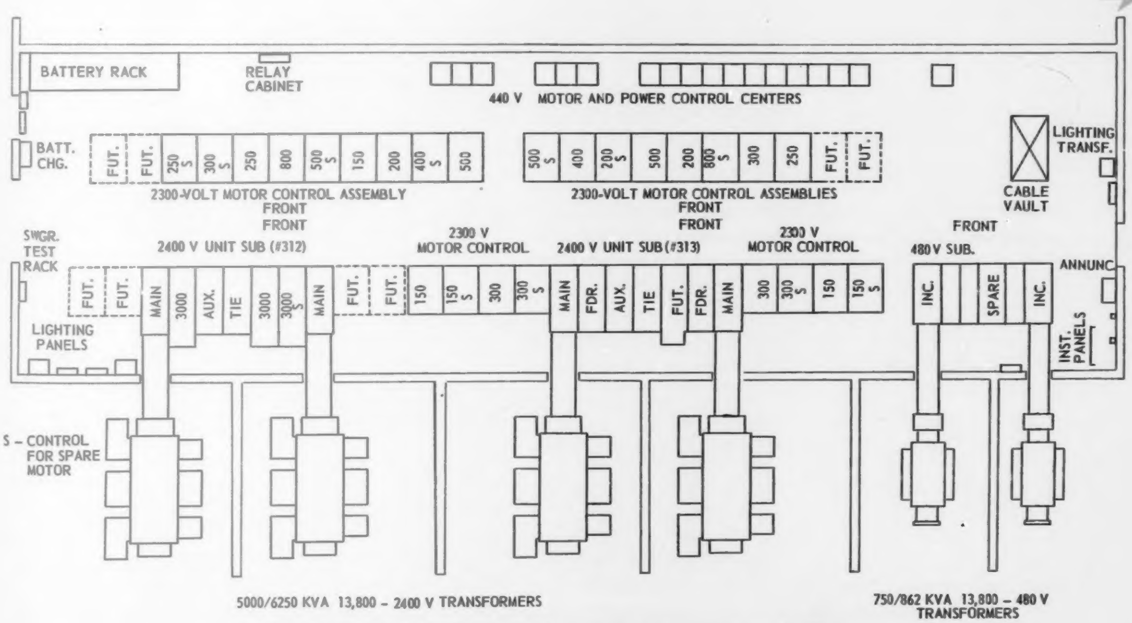
The Unifiner occupies an area 353 ft by 475 ft, the Hydrogen plant 381 ft by 475 ft. All of the power in this 8 acres of plant is supplied from Switch House 31, shown in Figure 12, located about midway between the two units along one edge of the plot.

Unifining is a process in which the sulphur is removed from the incoming raw petroleum feed stock by treatment with hydrogen under a combination of heat, pressure, and catalytic reaction. Desulphurization upgrades distillates by increasing octane ratings and reducing fuel burning odor problems. It also improves the efficiency of subsequent refining processes. At the Tidewater plant, about 60 percent of the total volume of the liquid product flowing through the refinery, plus some 30,000,000 cu ft per day of hydrogen (derived from a product from the crude in the hydrogen unit), is processed in the Unifiner. Most of the liquid feed comes directly from the crude unit.

After passing through the maze of pumps, heaters, reactors, fractionating towers, and condensers which make up the five parallel trains in the desulphurizing process, about 55 percent of the output is fed directly to the final product fuel blending unit. The remaining desulphurized product is mostly gasoline and naphtha fractions that must be further processed before final blending into various gasoline grades.

Most of the hydrogen used in Unifining is converted to hydrogen sulphide, from which sulphur is recovered for shipment. The Delaware Flying A Refinery has the largest sulphur recovery unit in the world, and when operating on mideastern oil will produce about 340 tons of sulphur for shipment daily, all extracted from the crude.

Obviously, any shutdown in the process handling such a large portion of the refinery's throughput could become very expensive. Furthermore, any loss of power to compressors, cooling pumps or lubricating pumps could present serious hazards. Thus in planning the electrical and control system for Switch House 31, every possible combination of failure had to be considered to make continuity of operation a certainty.



LAYOUT OF TYPICAL SWITCH HOUSE shows convenient arrangement. Auxiliary cubicles in switchgear were found to be more economical than angular ducts from transformers outside. Distance between transformers was fixed. **(FIGURE 12)**

THE STORY OF SWITCH HOUSE 31 Cont.

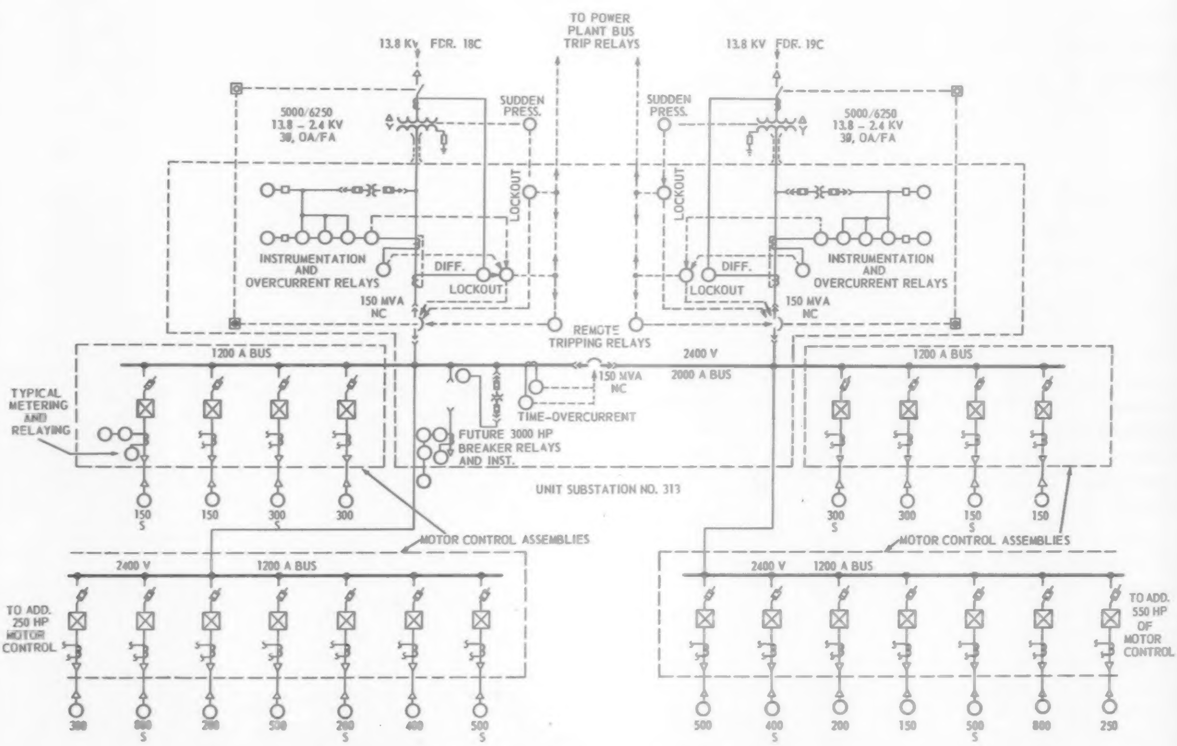
A simplified single line diagram of one of the substation and motor control assemblies in Switch House 31 is shown in Figure 13. In the case of a failure in the 2400 volt switchgear bus, the normally closed tie breaker opens, dropping power from all of the motors on that half of the bus. However, the automatic control on the individual component drives puts an alternate drive supplied from another feeder into service immediately. Failure of an individual motor or cable would open only that contactor or breaker and an individual spare motor would be switched into service immediately.

While the normal supply for lube oil pressure for the bearings of the important compressors is a motor driven pump, an automatic fail-safe control connects a spare pump, turbine-driven, into the lube oil circuit should the power to both incoming feeders somehow fail. In other emergencies such as one that might occur when a liquid product pump bearing fails, another automatic control, fail-safe and operating by compressed air, connects a standby pump driven by a spare motor connected via different control, switchgear and cables, all the way back to a different power plant bus.

Altogether there are 63 motors in this one section of the plant with horsepower ratings from 1½ to 3000. Seventeen of these are 300 horsepower or above. All of this power (actually far more kilowatts than many big factories require) is controlled in the 26 ft by 89 ft concrete block switch house.

The degree of electrification at the Delaware Flying A Refinery is well illustrated in the processes controlled by this switch house. Most refineries built up to this time have used turbines for virtually all main drives, but careful economic study showed here that with power available at attractive rates, it was not economical to use turbine drives, except where the exhaust steam will be reused.

The turbine drives in the two process units include a 4700 hp operating turbine driving a gas compressor, and 10 smaller turbines ranging from 7½ to 250 hp, as spare drives. There are 43 operating motor drives totaling 11,200 hp, with 21 relying on electrical spares.



SINGLE LINE DIAGRAM of one of 2400-volt substations installed in Switch House 31 shows interconnections and normal breaker positions. Remote tripping relays open breakers at switchyard bus in case of fault in feeder circuit. **(FIGURE 13)**

TUBE-COOLED DESIGN for the larger motor ratings were used extensively throughout the refinery to reduce hazards, simplify maintenance and insure long service life. About two-thirds of a mile of copper alloy heat exchanger tubes were used in this typical motor. **(FIGURE 14)**

Motors for the DELAWARE FLYING A REFINERY

by **G. W. BOTTRELL**
Senior Engineer
Electrical Dept.
C. F. Braun & Co.
and
D. E. STEELE
Los Angeles Office
Allis-Chalmers Mfg. Co.

Hundreds and hundreds of motors — most of them big — were needed to keep the refinery in production. Here is how the motors were selected.

IN PLANNING an industrial layout the size of the Tidewater Oil Company's new Delaware Flying A Refinery, the choice of what types of equipment to use is interlinked with countless other decisions, each one of which may be affected by a change in one of the factors. It is obvious that switching from turbine to motor drive on one big compressor might change the size of an entire switch house, or conceivably the total number of switch houses. By the same reasoning, a shift from synchronous to induction machines could bring about a major reshuffling of plans. Actual experience with hundreds of refineries and chemical plants enables the consultant to discard readily, from further study, combinations which are obviously uneconomical or of marginal value.

In selecting motors for the Tidewater refinery, the first step taken was an economic study to select operating voltages, matching costs of transformers, distribution switchgear, motor starters, cables, along with that of the different motors themselves. As a result of this study, it was decided that motors 125 hp or smaller should be operated on 440 volt power and all larger motors on 2300 volt power. Finally installed, there were 3—3000 hp motors, 9—2000 hp motors, 2—1000 hp motors — and over 400 motors ranging from three-quarters hp to 800 hp.

In proceeding with the study, it became evident that the motors required fell into a few well defined groups which could be given individual consideration.

Centrifugal pump drives

The first group consisted of direct connected, horizontal, totally-enclosed, fan-cooled, squirrel-cage induction motors driving high speed centrifugal pumps. These units might be bracketed in horsepowers ranging from 1 to 1000 and at speeds of 1800 and 3600 rpm. The motors of this group chosen for operation in all areas of the refinery were of the TEFC "totally-enclosed, fan-cooled" type equipped with bronze fans. Fabricated stainless steel fans were used above 800 hp. Other mechanical modifications included bronze heat exchanger tubes for the tube type motors, cast-iron conduit boxes, chemical paint, chemical insulation, grease lubricated ball bearings, on the smaller motors and oil lubricated sleeve bearings on the larger. To provide additional protection against rapid and severe temperature changes causing condensation of moisture inside the motors during shutdown periods, space heaters were specified for all 2300 volt motors.

Compressor drive motors

The second group of motors consisted of approximately 20 large slow-speed drives for reciprocating compressors. These units had horsepower ratings ranging from 200 through 3000 in speeds 600 rpm and below. The selection of these motors required more study than the first group because of the greater potential effect on the power dis-

tribution system of the refinery. As the project progressed, it became apparent that tradition favored and recommended the use of synchronous motors as drives for large reciprocating compressors, because of their inherent low cost and their higher operating efficiency and power factor.

The recommendations of the compressor manufacturers were turned over to the electrical design group for evaluation. In spite of the well established tradition, careful study showed, from the overall viewpoint, induction machines offered the most important advantages, particularly in simplicity and reliability of control. These factors became extremely important in a plant like the Delaware Flying A Refinery, which depends so heavily on continuity of service for efficient and profitable operation, particularly when a relatively large number of drives in the plant are electrically powered. As part of the survey, a very complete cost analysis was made of both synchronous and induction motors in various types of enclosures. Some of the additional costs chargeable to synchronous machines in refinery service included:

1. Dc excitation (motor-generator set with allied control).

2. Field application panel required for control.

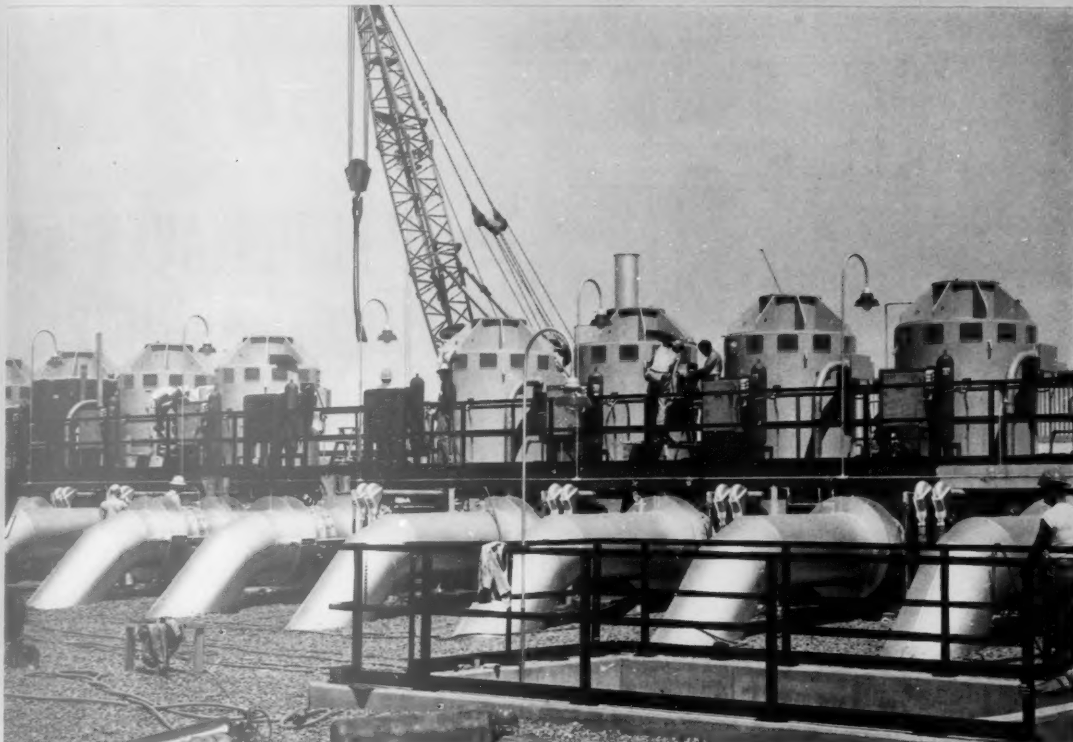
3. Additional wiring and conduit required between motors and exciters (exciters would have to be mounted in pressurized switch houses because of the semi-hazardous areas in which the compressors are installed).

4. An automatic unloading valve for the compressor (required because of the inherently low torque characteristics of a synchronous motor which would prevent reacceleration after voltage dips).

These considerations virtually wiped out the advantage of the synchronous motor in low first cost. A review of the advantage brought through power factor correction showed that the generators in the power station were rated at 85 percent P.F. Any load power factor of this value or above realizes the full capability of the generators. And this P.F. value could easily be maintained with induction motor drives. There would still, of course, be a slight advantage in additional available transformer capacity and higher system efficiency by utilizing the high power factor load of synchronous motors.

Synchronous motors had other characteristics that were particularly undesirable under the premises on which the refinery was being designed. Small motor-generator sets for excitation of a localized group of synchronous machines would require complicated control and automatic throw-over equipment to provide desired reliability, since the motors would be operating from a 2400 volt spot network system, whereas the exciters would be supplied with power from a 480 volt secondary selective system. Furthermore, upon momentary loss of voltage in the power system, synchronous motor control must disconnect the field supply, connect a discharge resistor across the field, and wait until the field voltage has decayed to at least

MOTOR DRIVES FAR OUTNUMBERED STEAM throughout most of the refinery, possible because of the plant's extremely dependable modified spot network distribution system. **(FIGURE 15)**



FINISHING TOUCHES were being put on the main river water pump drive installation when this photo was taken. Photo of motors during installation is shown on pages 18 and 19. **(FIGURE 16)**

25 percent voltage before power can be reapplied. This results in a much greater reduction in speed for a synchronous motor compared with an equivalent induction motor. This plus the extra time required for synchronous motors to reaccelerate and reach synchronism adds up to a considerably larger outage time for each fault.

These characteristics made it doubtful whether synchronous motor drives could ride through severe voltage dips without shutting down critical processes vital to refinery operation for short periods of time.

Because there were so many points in the refinery where any shutdown was to be avoided, and because economic advantages were negligible, it was decided to use squirrel-cage induction motors throughout the plant.

Large motors gas filled

In selecting the type of enclosure, cost comparisons showed that there was very little difference in the price of totally-enclosed inert gas filled motors and totally-enclosed fan-cooled motors below 1000 hp. However, above that size the gap between the prices widened appreciably, with the totally-enclosed fan-cooled motor becoming extremely expensive. It was therefore established that all motors 1000 hp and below would be furnished as totally-enclosed fan-cooled units and most motors above 1000 hp would be totally enclosed inert gas filled.

The totally-enclosed inert gas filled motors were provided with double-walled tube coolers, liquid level alarm, low water flow alarm, low gas pressure alarms, stator temperature detector alarms and other safety devices to increase their operation reliability.

River water pump motors

Special consideration was given to the group of nine 2000 hp, 600 rpm vertical centrifugal pump motors. These units were to be installed in the River Water Pumping Station on the Delaware River. These motors were key factors in the operation of the entire refinery, since almost all processes must shut down immediately if the cooling water supply should fail.

Standard practice has been to select weather-protected motors for installations such as this. However, operating experience of the Tidewater engineers led them to prefer a totally-enclosed motor, preferably a forced-air-cooled design. However, because of the size and weight of the housing required which must be entirely supported by the pump, design engineers soon found that this was impractical. On this basis, it was decided that totally-enclosed fan-cooled motors be installed. These nine units are among the largest totally-enclosed motors in physical size ever built.

Analyzing TRAVELING WAVES with AC CIRCUIT PRINCIPLES

by **A. H. KNABLE**
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Allis-Chalmers Mfg. Co.

This is the first of two articles dealing with a time-saving procedure for solving traveling wave problems.*

AN ELEMENTARY ANALYSIS of lightning and switching surges can save time both in the design of transmission and distribution equipment and in system planning. How much surge protective equipment is needed and where it is to be placed are questions that can be answered simply by converting traveling wave data to fundamental alternating-current circuit theory.

There are three steps involved in the transition from traveling wave theory to basic ac circuit theory.

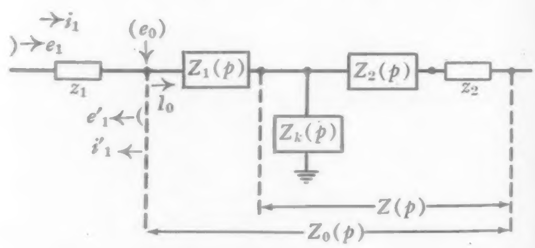
1. The conversion of the traveling wave voltage into an alternating-current circuit voltage.
2. Establishment of circuit boundaries.
3. Determination of a proper interpretation of the voltage to be calculated in the system.

* The second article, entitled "Short Cuts in Surge Analysis," will appear in the 1st Quarter, 1957 *Electrical Review*.

Traveling wave voltage is converted

One might ask, what is accomplished by analyzing the traveling waves with alternating-current circuit theory? Basically, the method of solution is simplified because analysis is made in familiar terms and procedures.

The following is a derivation converting the traveling wave voltage to an alternating-current circuit voltage:



SURGE is shown impinged on a generalized circuit. **(FIG. 1)**

Basic equations: (Ohm's Law)

$$\frac{e_1}{i_1} = z_1 = \text{incident (incoming) wave}$$

$$\frac{e'_1}{i'_1} = -z_1 = \text{reflected wave}$$

Developed equations:

$$i_1 + i'_1 = I_0 = \left(\frac{e_1 - e'_1}{z_1}\right) \text{ by } \Sigma i = 0 \qquad (1)$$

$$e_1 + e'_1 = e_0 = Z_0(p) I_0 \text{ by superposition} \qquad (2)$$

Symbols Defined:

1. $(e)\rightarrow$ — calculated voltage at point indicated
2. $)\rightarrow e$ — wave voltage
3. $e\uparrow$ — circuit voltage
4. $|e|$ — absolute value
5. $-\boxed{Z(p)}-$ a lumped parameter containing R, L, and C (any combination) in the transient form, where the p operator replaces the steady-state operator ω. For example, current-limiting reactors and static or rotating machines might be represented as lumped parameters.
6. $-\underset{z}{\square}-$ a distributed parameter of surge impedance Z. For example, overhead lines and cables, or rotating machines might be represented as distributed parameters. $z = \left(\sqrt{\frac{L}{C}}\right)\ \Omega.$

From Equations (1) and (2)

$$\frac{e_1 + e'_1}{Z_0(p)} = \frac{e_1 - e'_1}{z_1} \tag{3}$$

$$\text{thus } e'_1 = \left(\frac{Z_0(p) - z_1}{Z_0(p) + z_1}\right) e_1 \tag{4}$$

From Equations (2) and (4)

$$e_0 = \left(\frac{2Z_0(p)}{Z_0(p) + z_1}\right) e_1 \tag{5}$$

From Equation (4)

$$i'_1 = \frac{-e'_1}{z_1} = -\left(\frac{Z_0(p) - z_1}{Z_0(p) + z_1}\right)\frac{e_1}{z_1}$$

$$= -\left(\frac{Z_0(p) - z_1}{Z_0(p) + z_1}\right) i_1 \tag{6}$$

From Equations (1) and (6)

$$I_0 = \left[1 - \left(\frac{Z_0(p) - z_1}{Z_0(p) + z_1}\right)\right] i_1 = \left(\frac{2z_1}{Z_0(p) + z_1}\right)\frac{e_1}{z_1}$$

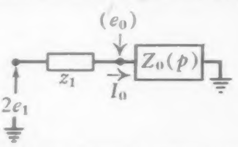
$$= \left(\frac{2}{Z_0(p) + z_1}\right) e_1 \tag{7}$$

Substituting $Z_0(p)$ of Equation (7) into Equation (5) yields

$$e_0 = \left[\frac{2(2e_1 - I_0 z_1)e_1}{[(2e_1 - I_0 z_1) + I_0 z_1]}\right] = (2e_1 - I_0 z_1) \tag{8}$$

From Equation (8): $\left\{ e_0 = (2e_1 - I_0 z_1) \right\}$

The circuit representation of Equation (8) is:



VOLTAGE $2e_1\uparrow$ has replaced voltage $)\rightarrow e_1$. **(FIG. 2)**

Thus Equation (8) and its circuit representation complete the transition from traveling wave theory to alternating-current circuit theory.

Circuit boundary is determined

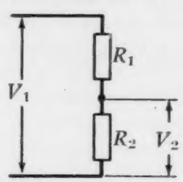
The Circuit Proper—When analyzing large systems that have ties with adjacent systems, a complete circuit representation is unwieldy and the point at which the circuit proper ends must be determined. A traveling wave voltage at the substation is a function of the line struck by lightning, the lumped parameters of the substation equipment attached to this line, and the lines leading from this substation. Any parameters attached to the far end of the lines leading from the substation are too remote to be of any immediate concern because it takes time for a wave to reach the far end. Even though the lines are short, the element of time is an important factor.

Reflections—Not until reflections are considered do these remote parameters enter into the analysis, and even then these parameters are negligible if the surge attenuation (decay) is great enough.

Depending on the length of line and its characteristics, there is a good possibility that the attenuation will be so great that the reflected waves will be negligible, and thus the remote parameters seldom enter into the analysis. In either case, whether the reflection is immediate or remote, it should be remembered that the *element of time* as well as magnitude is a determining factor when establishing a circuit boundary for the calculation of the initial surge. The reflection of surge energy from a transformer is similar to a wave of water reflected from a wall.

System voltages are calculated

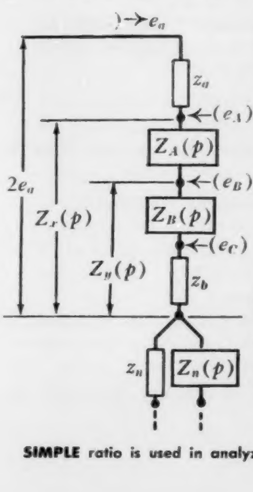
After the circuit has been established it can be analyzed using the voltage-impedance ratio found in alternating-current circuit theory:



$$\frac{V_2}{V_1} = \frac{R_2}{R_1 + R_2}$$

CIRCUIT illustrates a simple voltage impedance ratio. **(FIG. 3)**

A circuit to illustrate the use of the voltage-impedance ratio in analyzing surge phenomena using the equivalent circuit is shown in Figure 4.



$$\leftarrow(e_A) = \left(\frac{Z_x(p)}{z_a + Z_x(p)}\right) Ze_a$$

$$\leftarrow(e_B) = \left(\frac{Z_y(p)}{z_a + Z_x(p)}\right) Ze_a$$

$$\leftarrow(e_C) = \left(\frac{z_b}{z_a + Z_x(p)}\right) Ze_a$$

The above equations are independent of the impedances connected beyond the second surge impedance encountered in the circuit.

SIMPLE ratio is used in analyzing surge phenomena. **(FIG. 4)**

The incoming surge is $)\rightarrow e_a$ which is replaced by its equivalent $2e_a\uparrow$. The voltages at the various points in the circuit are expressed as shown.

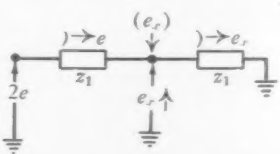
Proper interpretation of the voltages calculated—Now that the system can be established and the voltages at the various parts of the system can be evaluated, the next step is to interpret these voltages properly. Injecting some conditional statements will help to interpret these voltages and to better appreciate the purpose of the proofs that will follow. Is the circuit voltage designated by the symbol $(e)\rightarrow$ a representation of (*a*) the wave voltage $)e\rightarrow$ magnitudes at the various points, or (*b*) the equivalent alternating-current circuit voltage $e\uparrow$ magnitudes?

If (*a*) is true, then the equivalent alternating-current voltages are represented by doubling the magnitude of the calculated voltages. But if (*b*) is true, then the wave voltages are represented by halving the magnitude of the calculated voltages.

The above reasoning would be sound, based on the derived relation $)\rightarrow e \equiv 2e\uparrow$ except that a surge can exist only on a surge impedance. If the surge is passing through lumped parameters, it is not recognized as a traveling wave. It is only an alternating-current circuit potential for that instant of time. Upon leaving these lumped parameters, it once more becomes identified as a surge. Keeping this in mind and returning to the question of proper voltage interpretation, one is led to the conclusion that if the calculated voltage $(e)\rightarrow$ is a representation of the wave voltage and if the calculated voltage is at a point where a wave passes into a lumped parameter, the magnitudes of both the wave voltage $)\rightarrow e$ and the equivalent alternating-current circuit voltage $e\uparrow$ are equal to $(e)\rightarrow$. On the other hand, if the calculated voltage $(e)\rightarrow$ is at a point where a wave passes into a surge impedance, the magnitude of the wave voltage $)\rightarrow e$ is still $(e)\rightarrow$, but the equivalent alternating-current circuit voltage is twice $(e)\rightarrow$.

Theory is proved

Supporting these conclusions, *first* is the proof that the magnitude of $(e_x)\rightarrow$ is the magnitude of the wave voltage $)\rightarrow e_x$.



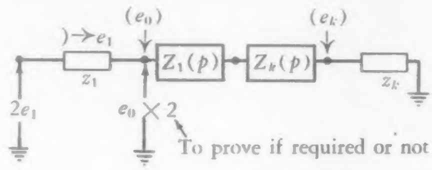
MAGNITUDES of wave and calculated voltages are equal. (FIG. 5)

Using circuit theory: The voltage at point x is:

$$\leftarrow(e_x) = \left(\frac{z_1}{z_1 + z_1}\right) 2e = e$$

Using wave theory: Noting that $z_1 = z_1$, that is, x is not a real transition point, tells us that $)\rightarrow e_x$ is the same wave as $)\rightarrow e$. Since by circuit theory $|(e_x)\rightarrow| = |e|$, and by wave theory $|)\rightarrow e_x|$ must be $|e|$, the $(e_x)\rightarrow$ calculated by circuit theory is $)\rightarrow e_x$. This conclusion eliminates the confusion of whether the $(e)\rightarrow$ voltages calculated are to be interpreted as $|e|$ being wave magnitude, or as $|2e|$ being circuit magnitude. As was proven, earlier in the paper, the conversion of $)\rightarrow e \equiv 2e\uparrow$ holds at all points of the circuit where a wave enters a surge impedance.

Second is the proof that the magnitude of $e\uparrow$ is equal to the magnitude of $(e)\rightarrow$ when the surge enters a lumped parameter.



CALCULATED voltage magnitude equals circuit voltage. (FIG. 6)

(1) Determine $(e_k)\rightarrow$ by proven means, using $2e_1$ and voltage-impedance ratio.

$$(e_k)\rightarrow = \left(\frac{z_k}{z_1 + Z_1(p) + Z_k(p) + z_k}\right) 2e_1 \leftarrow \text{Ans.}$$

(2) Determine $(e_k)\rightarrow$ by way of $(e_0)\rightarrow$ to $2e_1\uparrow$.

$$(e_0)\rightarrow = \left(\frac{Z_1(p) + Z_k(p) + z_k}{z_1 + Z_1(p) + Z_k(p) + z_k}\right) 2e_1$$

$$(e_k)\rightarrow = \left(\frac{z_k}{Z_1(p) + Z_k(p) + z_k}\right) \underset{\substack{\uparrow \\ \text{Assume required}}}{2e_0}$$

$$\therefore (e_k)\rightarrow = \left(\frac{z_k}{Z_1(p) + Z_k(p) + z_k}\right) \left(\frac{Z_1(p) + Z_k(p) + z_k}{z_1 + Z_1(p) + Z_k(p) + z_k}\right) 4e_1$$

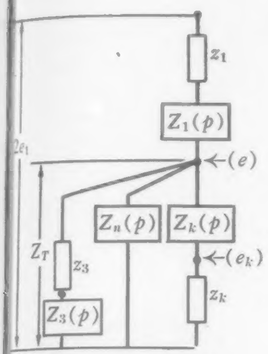
$$\therefore (e_k)\rightarrow = \left(\frac{z_k}{z_1 + Z_1(p) + Z_k(p) + z_k}\right) 4e_1$$

Since the proven expression for $(e_k)\rightarrow$ contains $2e_1$, and the expression by way of $(e_0)\rightarrow$ contains $4e_1$, the assumed required multiplier "2" for the circuit voltage $e_0\uparrow$ is not required. This is in agreement with the statement that when the surge enters a lumped parameter, the circuit voltage $e\uparrow$ is equal to the calculated voltage $(e)\rightarrow$.

We may now conclude that, first, the magnitude of $(e)\rightarrow =)\rightarrow e = 2e\uparrow$ when entering a surge impedance, and second, the magnitude of $(e)\rightarrow = e\uparrow$ when entering a lumped parameter.

A brief consideration of two further conditions to bring out a few additional factors in interpreting the calculated voltages remains.

1. If a circuit has a system with parallel branches, what is the circuit voltage at $(e_k)\rightarrow$?



PARALLEL BRANCHES are analyzed. **(FIG. 7)**

To find e_k, first determine junction potential e.

$$e = \left(\frac{Z_T}{z_1 + Z_1(p) + Z_T}\right) 2e_1$$

Then express e_k in terms of e.

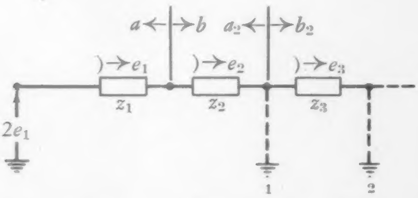
$$e_k = \left(\frac{z_k}{z_k + Z_k(p)}\right) e$$

Then substitute $e = f(e_1)$ into e_k.

$$e_k = \left(\frac{Z_T}{z_1 + Z_1(p) + Z_T}\right)\left(\frac{z_k}{z_k + Z_k(p)}\right) 2e_1$$

In this case, we evaluated e_k so $(e)\rightarrow$ was interpreted as a circuit voltage. However, upon inspecting the circuit it will be noticed that there are both lumped and distributed parameters at point $(e)\rightarrow$. The lumped parameter dictating the circuit voltage is $|e|$, and the distributed parameter dictating the circuit voltage is $|2e|$. Now what is the circuit voltage at $(e)\rightarrow$? The answer is simply this: If the branch of the circuit with which one is concerned contains the lumped parameter, the circuit voltage is $|e|$. If the branch being analyzed contains the surge impedance, the circuit voltage is $|2e|$.

2. If the circuit contains a voltage which is beyond the second surge impedance encountered in the circuit, how do we determine this voltage?



VOLTAGE beyond second surge impedance is determined. **(FIG. 8)**

The circuit ends at the end of the second surge impedance; there e_2 must be determined before e_3 can be evaluated in terms of $2e_2$.

By ac circuit theory

$$e_2 = \left(\frac{z_2}{z_1 + z_2}\right) 2e_1$$

$$e_3 = \left(\frac{z_3}{z_2 + z_3}\right) 2e_2$$

$$e_3 = \left(\frac{2z_2}{z_1 + z_2}\right)\left(\frac{2z_3}{z_2 + z_3}\right) e_1$$

By traveling wave theory using refraction operators

$$b = \frac{z_2 - z_1}{z_2 + z_1} + 1 = \frac{2z_2}{z_1 + z_2}$$

$$b_2 = \frac{z_3 - z_2}{z_3 + z_2} + 1 = \frac{2z_3}{z_3 + z_2}$$

$$e_2 = be_1$$

$$e_3 = b_2 e_2 = b_2 b e_1$$

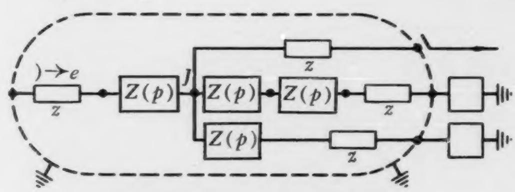
$$e_3 = \left(\frac{2z_3}{z_2 + z_3}\right)\left(\frac{2z_2}{z_1 + z_2}\right) e_1$$

Since the refraction operator method agrees with the alternating-current circuit theory method, the latter is verified.

Facts established

To summarize, the following points have been established:

1. A surge of magnitude $)\rightarrow e$ on a surge impedance z can be represented as a circuit voltage of $2e\uparrow$ when analyzing a system.
2. The boundary of the circuit for calculating the initial voltage at the junction point is the surge impedance on which the wave enters and the first surge impedance in each branch (in the case of parallel circuitry) which the wave encounters upon leaving the junction point.



BOUNDARIES are established. **(FIG. 9)**

3. The common voltage-impedance ratio avoids the use of reflection and refraction operators when the initial circuit voltage is desired.
4. The magnitude of the calculated voltage $(e)\rightarrow$ always represents the magnitude of the wave voltage $)\rightarrow e$, regardless of whether the wave enters a lumped or distributed parameter.
5. The magnitude of the wave voltage $)\rightarrow e$ and the magnitude of the circuit voltage $e\uparrow$ are equal when the wave enters a lumped parameter.
6. This analysis is concerned with the initial voltage at some point in the system. If a circuit is void of multiple reflections, the initial voltage will also be the final voltage. However, most systems are not free from multiple reflections; therefore the final voltage will be obtained from the resultant of the initial plus the sum of the reflections. These reflections can be determined very simply by the use of a reflection lattice, which is nothing more than a systematic means of recording the reflections as they occur.

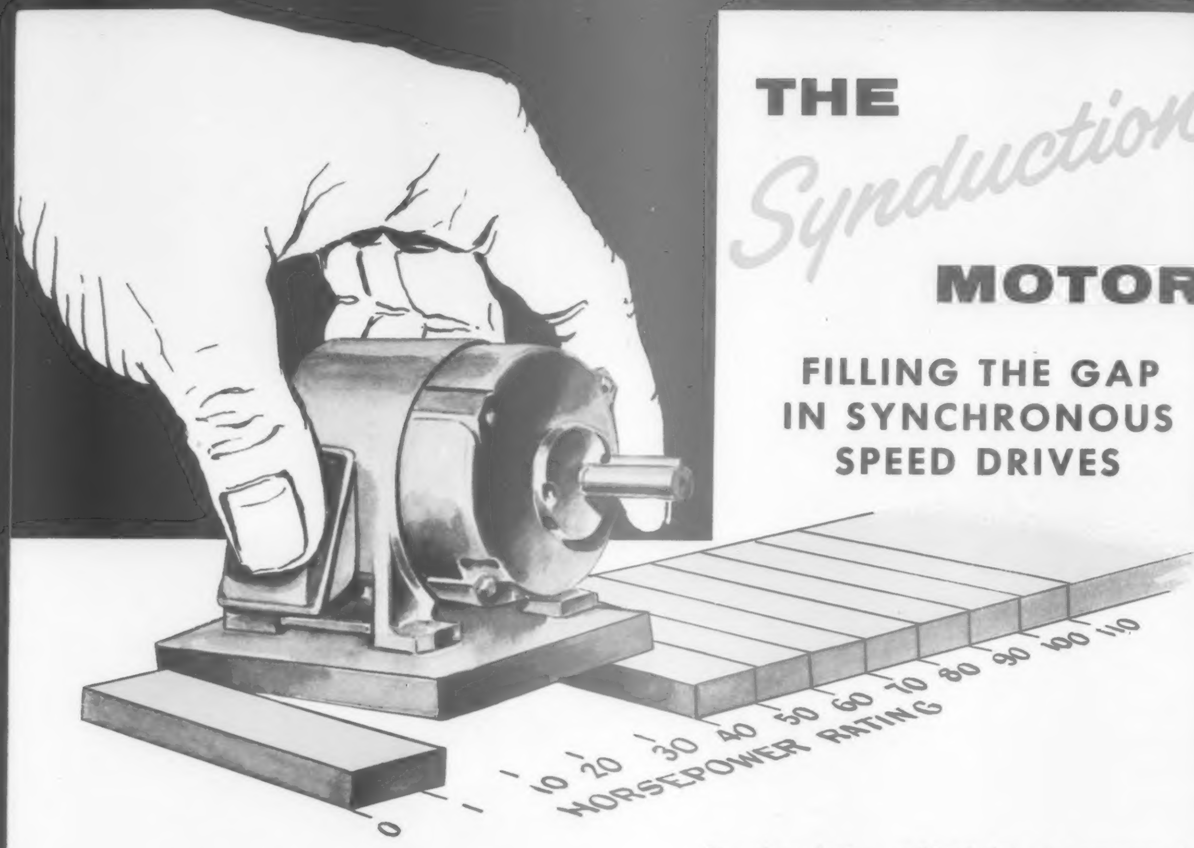
REFERENCE

Traveling Waves on Transmission Systems, L. V. Bewley, John Wiley & Sons, Inc., New York, 2nd edition, 1951.

275,000 GALLONS PER MINUTE of water from Cedar Creek (as it enters the Delaware River) will be circulated throughout the Tidewater Oil Company's new Flying A Refinery by these nine 2000 hp, 600 rpm motor driven pumps. Cooling water circulation, vital to almost every phase of the plant's operation, will account for about one-third of the total power needed by the refinery.

THE *Synduction* MOTOR

FILLING THE GAP IN SYNCHRONOUS SPEED DRIVES



by R. J. DINEEN
Electrical Dept.
Norwood Works
Allis-Chalmers Mfg. Co.

THE LONGFELT NEED for synchronous speed motors rated less than 50 hp and combining relatively high efficiency with reasonable initial cost, has led to the recent development of the *Synduction* motor. Combining squirrel-cage simplicity and ruggedness with constant speed regardless of load, this new motor provides equipment designers and plant engineers with an entirely new approach to many drive problems.

Essentially a greatly improved version of the reluctance-type motor, the *Synduction* motor attains synchronous speed without direct-current excitation. It has no slip rings, no brushes, no dc pole pieces, and no rotor windings. The yoke, housings, bearings, and three-phase wound stator are similar to those of a standard squirrel-cage induction motor.

Reluctance-type motors which operate at synchronous speed without dc excitation have been built for many years, but their extremely poor power factors and efficiencies have ruled them out almost completely for ratings above 10 hp, and have made them impractical for many applications requiring less than 10 hp.

In contrast, efficiency and power-factor characteristics of the *Synduction* motor make it practical for drives requiring as much as 40 hp.

By unique slotting combinations in the rotor core, the efficiency of the *Synduction* motor has been brought to a point where it now compares favorably with the efficiencies of standard induction machines. Power factors are still somewhat below standard induction motors, but improvement over conventional reluctance designs has been considerable.

Table I shows a comparison of typical motor performance characteristics for several different types of machines, rated 20 hp, 1800 rpm, three-phase, 60 cycles.

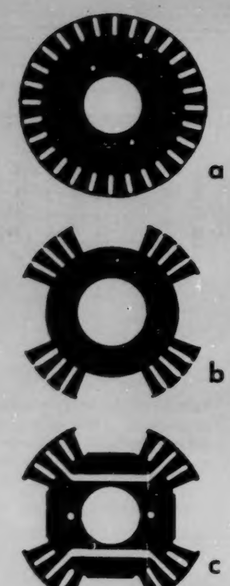
Typical rotor laminations for a standard squirrel-cage induction machine, a reluctance motor and a *Synduction* motor are compared in Figure 1. Squirrel-cage laminations shown in Figure 1*a* are stacked one on top of the other to obtain proper core length, and then the rotor bars, the end ring, and the ventilating fans are cast integrally on an aluminum die-casting machine. Figure 1*b* shows a rotor lamination typical of reluctance motor design; Figure 1*c* is a *Synduction* motor lamination. *Synduction* motor rotor laminations are stacked, and rotor bars, end rings and ventilating fans are aluminum die-cast in a manner similar to induction motor construction. Die-cast metal fills all of the voids in the *Synduction* rotor laminations, and the end result, shown in Figure 2, looks much like a squirrel-cage induction motor rotor. The old reluctance-type design did not have a die-cast rotor. Grooved portions on the surface of the rotor core were not filled. Figure 1*b* indicates the physical resemblance of a reluctance motor rotor to a salient-pole synchronous motor rotor.

Both the reluctance motor and the *Synduction* motor operate on the principle of presenting a low reluctance path to the direct axis flux and a high reluctance path to the quadrature axis flux. The high reluctance path sup-

	Synchronous Motors		Synduction Motor	Squirrel Cage Induction Motor	Reluctance Motor
	100% PF	80% PF			
Efficiency, percent	88	87	88	88	79
Power Factor, percent	100	80**	60†	88†	38†
Pull-out Torque, percent	150	200	175	...	150
Pull-in Torque, percent*	110	125	120	...	80-100
Locked-rotor Torque, percent	110	125	280	150	400
Locked-rotor Current in percent of Full Load amps	675	600	975	575	1050

** Lead † Lag * Based on 8 lb ft² load inertia

PERFORMANCE CHARACTERISTICS of a *Synduction* motor are compared with those of synchronous, induction, and reluctance motors. Data is based on 20-hp, four-pole, three-phase motors. **(TABLE 1)**



ROTOR LAMINATIONS typical of (a) induction, (b) reluctance, and (c) *Synduction* motors are arranged for comparison. **(FIGURE 1)**

presses the quadrature axis flux and produces the same effect as occurs in a dc excited salient-pole synchronous rotor.

Starting and speed characteristics defined

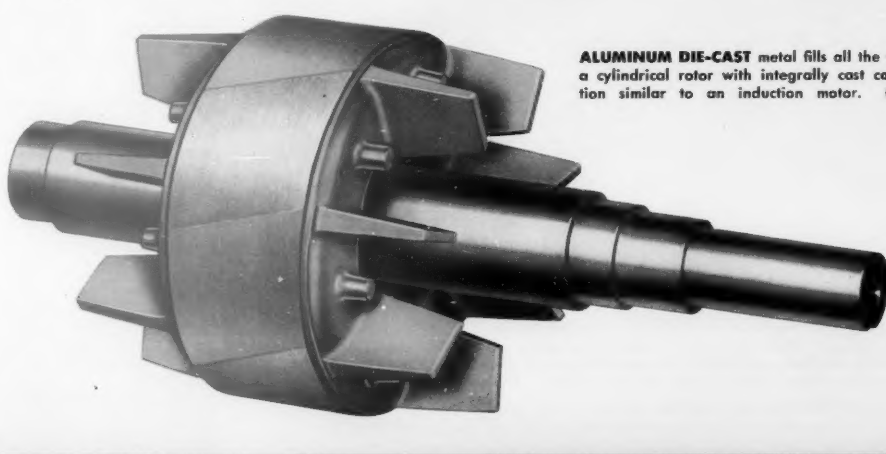
The *Synduction* motor builds up to its synchronous speed much like an induction motor. A typical speed-torque curve is shown in Figure 3. Starting torques for *Synduction* motors applied to normal inertia loads are in the order of 350 to 550 percent of the full-load running torque; pull-out torques, 160 to 200 percent of full-load torque; and pull-in torques, 110 to 140 percent of full-load torque. The pull-in torque of any *Synduction* motor is dependent strictly on the connected load and load inertia, as indicated by Figure 4.

When the load placed upon a *Synduction* motor exceeds pull-out torque, the motor will operate as an induction motor, as indicated by its speed-torque characteristic curve. However, *Synduction* motors are not designed to operate in the range above pull-out or even near the pull-out point except for short intervals.

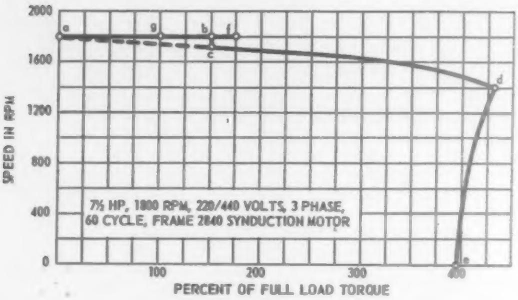
Open-type 40 C rise *Synduction* motors will have the same 15 percent service factor as standard induction machines. Totally enclosed, fan-cooled *Synduction* motors will have a service factor of 1.0. Almost any enclosure or mechanical configuration suitable for a standard induction machine, such as flanges, special insulations, or vertical construction, is equally suitable for *Synduction* motors.

Inrush currents for *Synduction* motors are normally rather high, usually between 750 to 1200 percent of full-load current. Also full-load current for a *Synduction* motor of a given rating will be somewhat higher than the full-load current for a standard induction motor of the same rating, because of the lower power factor. Consequently, the magnitude of inrush current for a *Synduction* motor will be appreciably higher than inrush current for an induction machine. However, in some special cases the motors can be built for part-winding starting to alleviate this condition.

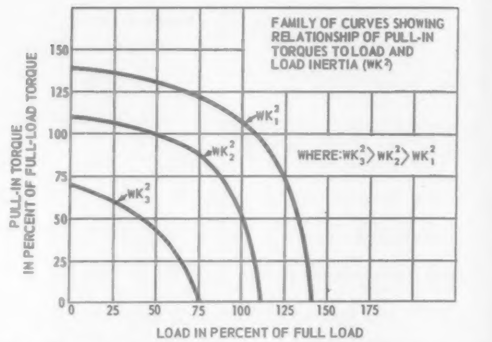
Because of these characteristics, when standard three-phase across-the-line starting equipment is applied, a starter one size larger than would be used for an induction motor of the same rating is required. Heater elements for overload protection should be selected on the basis of full-load current rating. Reduced-voltage starting and wye-delta starting, as well as full-voltage starting, may be used in connection with these machines, depending upon the driven load and the application.



ALUMINUM DIE-CAST metal fills all the voids, giving a cylindrical rotor with integrally cast cage construction similar to an induction motor. **(FIGURE 2)**



THIS TYPICAL SPEED-TORQUE curve shows starting point *e*, maximum torque point *d*, and points *c* and *b* (pull-in torque) at which synchronous speed is attained. Synchronous speed is maintained from *a* to *f* (pull-out torque). Point *c* is dependent on connected load enertia. (FIG. 3)



PULL-IN TORQUE must exceed load torque if the motor is to attain synchronous speed. With Wk^2_1 connected, pull-in torque is 110% at 100% load and motor will synchronize. With Wk^2_2 connected, pull-in torque is 50% at 100% load and motor will not synchronize. (FIG. 4)

Synduction motors will run at absolute synchronous speed so long as load does not exceed pull-out torque. Typical performance characteristics of efficiency, power factor, inrush current, and speed versus power output in horsepower are shown in Figure 7. *Synduction* motors are designed to stand variations in line voltage supply of plus or minus 10 percent without changing speed under full-load conditions. The accuracy of the speed will be just as good as the accuracy of the frequency supply source. However, there will be a different torque angle of operation for different loads on the machine.

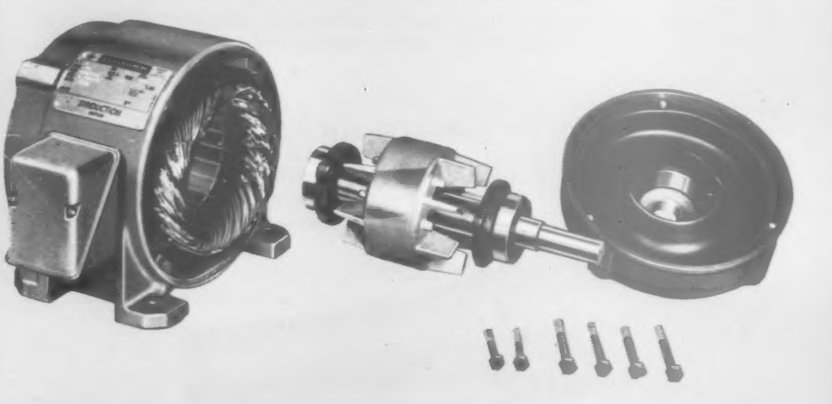
Torque angle is defined as the angle between the terminal voltage axis and the rotor pole axis. The amount of torque developed by a *Synduction* motor is related to the magnitude of this torque angle, as indicated by Figure 9. Under no-load conditions the torque angle will be very small and the rotor will produce a very small torque, just sufficient to overcome windage and friction of the motor and load. Under full-load conditions the torque angle will be appreciable, and the torque output of the motor will be equal to the torque required by the driven equipment. Figure 8 illustrates this principle for a two-pole machine.

Constant-speed applications

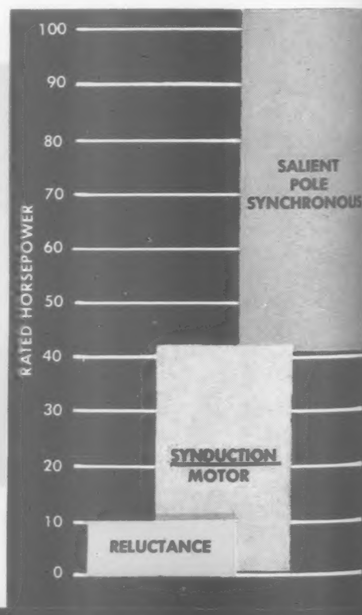
There are several constant-speed applications in which the use of the *Synduction* motor rather than the previously used induction machine has resulted in improved performance of the driven equipment or improved quality of the end product. For example, when it is used as the driving member for either 60 or 400-cycle motor-alternator sets, alternator output has shown improved characteristics. Unlike the *Synduction* motor, an induction drive motor, with its inherent slip characteristics, cannot maintain constant speed during changes in load on the alternator it is driving. Consequently, alternator output frequency varies.

The reason for using a *Synduction* motor as the driving half of a 60-cycle motor-alternator set is possibly not as obvious. Since the speed of the *Synduction* drive motor is dependent strictly upon input frequency, the frequency output of the alternator is obviously no better than the frequency of the supply line. In this case, the only reason for using a *Synduction* motor is to maintain constant voltage output, with constant load on the alternator terminals, despite varying voltage supply to the drive motor.

Since the *Synduction* motor runs at synchronous speed regardless of small variations in line voltage, the 60-cycle motor-alternator set acts as a line filter supplying a 60-cycle constant-voltage output from the alternator. An extremely stable power supply of this type is required by



SYNDUCTION MOTOR mechanical parts are identical to those of a standard induction motor, while electrical parts are similar. (FIGURE 5)



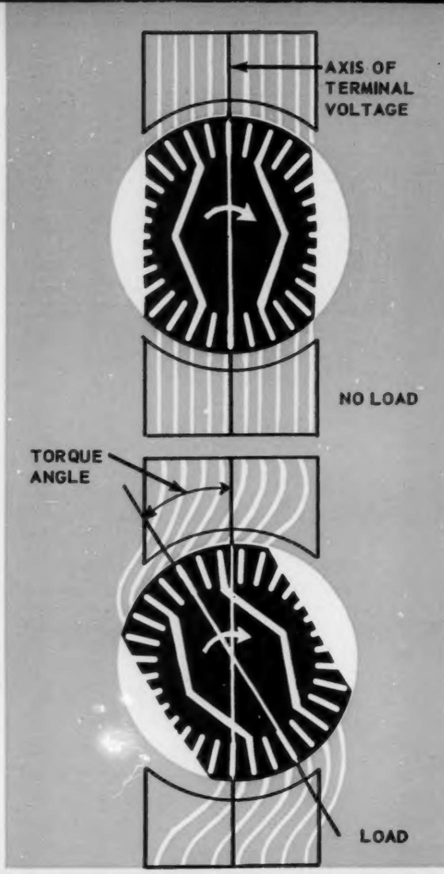
SYNCHRONOUS MOTOR SPEEDS in horsepower ranges previously not economically feasible are achieved by this new design. (FIGURE 6)

some sensitive electronic testing equipment, particularly that used for guided missiles, which cannot tolerate the normal line voltage fluctuations obtained from a standard power supply.

Synduction motors have been used in automatic or semi-automatic processes where a particular function must be synchronized with preceding and following operations. Many applications of this type are found in the food-processing and packaging industries. One specific example is a meat-slicing machine drive. Despite load variations resulting from variations in the consistency of materials being processed, a *Synduction* motor driving the slicing machine maintains constant speed, enabling synchronization of the slicing operation with succeeding packaging and preceding operations.

Positive displacement metering pumps or proportioning units are logical applications for this synchronous machine. These are normally low power requirement operations. When *Synduction* motors are applied, the output of the metering pump or proportioning unit is constant, regardless of changes in temperature which affect the viscosity of the liquid and therefore the load on the drive motor. Since drive motor speed is independent of load, the amount of liquid pumped remains constant.

These applications are representative of processes that require drives in the range of 1 to 40 hp and have the additional requirement that they must operate at synchronous speed regardless of the load imposed. Salient-pole synchronous machines in this horsepower range would normally be prohibitively expensive.



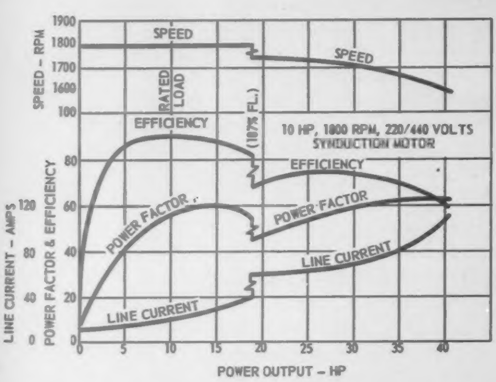
TORQUE ANGLE, formed by the terminal voltage and rotor pole axes, is minimum at no load, maximum at pull-out. **(FIGURE 8)**

Variable-speed operation of *synduction* motors

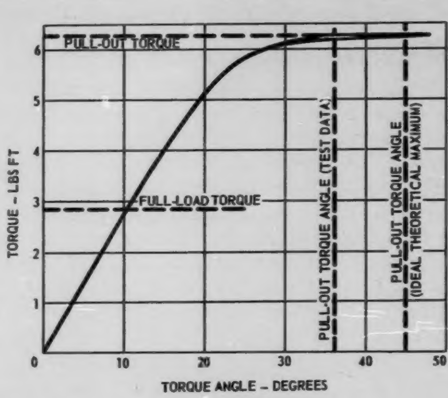
Once a given machine is wound for a specific number of poles, its output speed depends strictly upon input frequency. By varying the input frequency to the motor, output speed can be varied and the motor will run at the synchronous speed for the frequency supplied, regardless of the load imposed upon the motor. Consequently, a range of precise speed settings that will be unaffected by the load on the machine can be obtained.

There are several means of obtaining variable frequencies. A salient-pole synchronous alternator driven at variable speeds will produce a variable-frequency output —so will a frequency converter unit with either constant or variable-frequency excitation, driven at variable speeds. Both of these methods have been used to obtain a variable-frequency source for *Synduction* motors.

Typical of applications requiring this type of variable-speed drive is one found in the synthetic textile industry. Because of the horsepower range and the extreme accuracies required in processing synthetic textile fibers, mechanical speed-changing devices have often been used. This process may require as many as 90 to 100 machines. Synchronization of all units in such a group must be



THESE TYPICAL *SYNDUCTION* motor performance curves are based on results obtained from 10 hp, four-pole machines operating on 440 volts. **(FIGURE 7)**



AS LOAD INCREASES, *Synduction* motors maintain synchronous speed up to pull-out point, but torque angle increases. **(FIGURE 9)**

THIS *SYNDUCTION* MOTOR driven set supplies high accuracy, variable-frequency power to several *Synduction* motors, enabling the motors to run at variable speeds but in synchronism with each other regardless of their speed. **(FIGURE 10)**

maintained over a wide range of preset speeds. These requirements are satisfied very well by using *Synduction* drive motors at each of the 90 to 100 stations along the process line and supplying them from a single variable-frequency alternator.

In applications of this type, drift or speed change after a given setting must not exceed plus or minus one-tenth of 1 percent for steady-state load conditions over the entire range of speed settings. This high degree of accuracy is obtained by using a *Synduction* motor driving a variable-frequency salient-pole alternator through a suitable set of double motion control V-belt sheaves and fixed pitch drive sheaves.

Speed ranges as high as 15 to 1 have been accomplished using this arrangement. However, this speed range is not obtainable without changes in the fixed pitch drive. A wide range drive which will give a 3 to 1 speed range without necessitating sheave changes while producing accuracies nearing plus or minus one-tenth of 1 percent under steady-state load conditions is now being developed. For applications requiring even wider ranges of speed, but not requiring this high degree of accuracy, other types of mechanical speed-changing devices less restricting than the 3 to 1 speed range of V-belt drives can be used.

Used as a component in a control system

The *Synduction* motor is being used as a component in a system designed to control water-wheel generator speeds. In this control system, a permanent-magnet alternator is coupled directly to the shaft of the water-wheel generator. This permanent-magnet generator supplies a *Synduction* motor which in turn drives a flyball governor. The permanent-magnet generator, since it is coupled directly to the water-wheel generator, will put out a higher frequency than normal should the water-wheel generator tend to speed up above its desired speed. This higher frequency is then fed to the *Synduction* motor driving the flyball governor, causing an increase in speed of the *Synduction* motor. The flyball governor in turn tends to close the inlet valve to the turbine runner, thus cutting down the unit's speed.

Should turbine speed fall below the desired level, the permanent-magnet generator output frequency drops off, thus lowering the speed of the supported *Synduction* motor. This causes the flyball governor to open the valve controlling the flow of water to the turbine runner, thus increasing turbine speed to the desired level.

Supporting sets are larger than normal

There are several problems involved in sizing the alternator and drive motor to support a *Synduction* motor. Since a *Synduction* motor requires high inrush current when starting on full voltage, the supporting alternator will have to be designed to handle the heavy inrush currents during the starting and accelerating period. In some cases, therefore, alternator sizes may seem large when compared to the supported equipment.

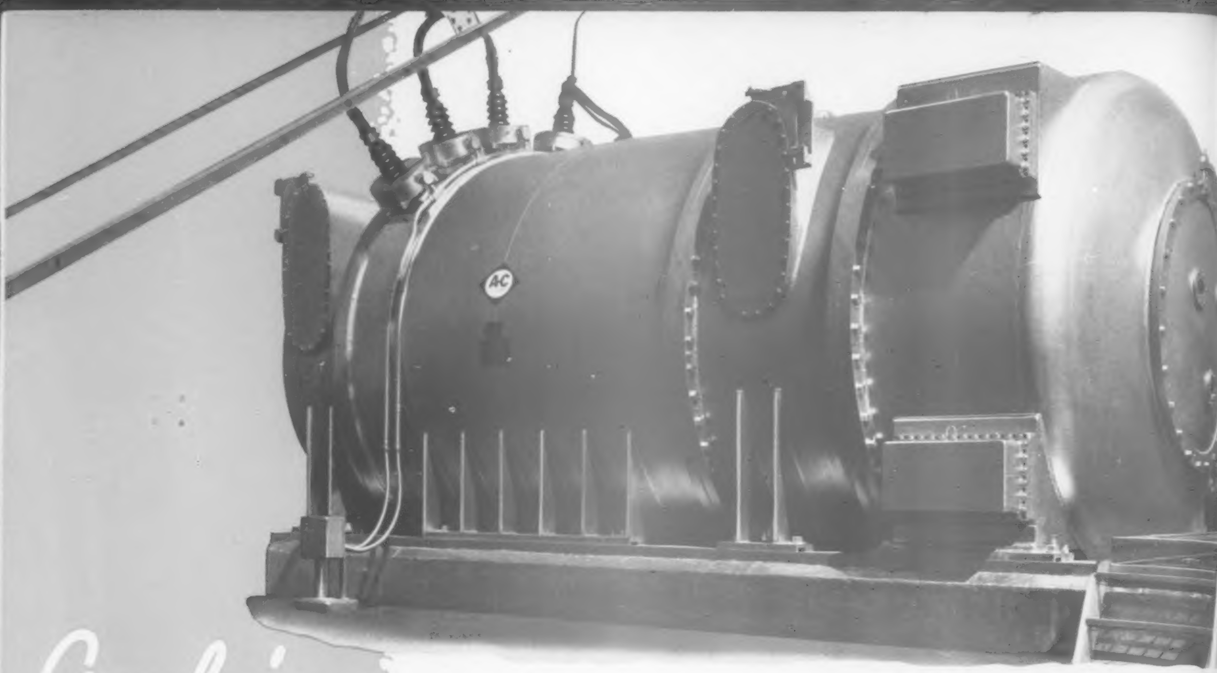
Where more than one *Synduction* motor is supported from a given alternator, this problem will be increased if all motors must be started simultaneously. The worst condition that will normally exist will occur when all motors but one are running at full load, and the one remaining motor is started. In this case the alternator would have to maintain at least 85 percent of rated terminal voltage during the start-up of the final motor so that the motors already being supported from the alternator terminals would not pull out of synchronism.

To alleviate this problem during the start-up period, a unique closed loop method of starting the supported motors has been developed. In this starting procedure, it is not necessary to start the supported motors across the terminals of the alternator under full-voltage conditions. With all of the machines at rest, the supported motors tied directly to the output terminals of the alternators and the alternator fully excited, the main drive motor for the variable-frequency alternator is started. Under a set-up of this type the currents drawn by the *Synduction* motors during the starting and accelerating periods never exceed approximately 125 percent of the normal rated full-load current. With this starting method the alternator can be sized more on the basis of supported motor full-load conditions than on the basis of supported motor inrush conditions. A separate source of dc excitation for the alternator fields is of course necessary.

Normally, the voltage applied to variable-frequency motors is supplied on the basis of constant volts per cycle; that is, if at 60 cycles the voltage is 440 volts, at 30 cycles the voltage will be 220 volts. The lower limit of frequency operation is normally considered to be about 10 cycles per second, and at these low frequencies the voltage supplied must be approximately 10 to 15 percent higher than the normal constant volts per cycle.

Although introduced only this year, the *Synduction* motor has already proven itself as a practical and economical drive for numerous applications. Because it combines constant speed regardless of load with squirrel-cage simplicity and ruggedness—in ratings for which no other synchronous motor is economically feasible—the *Synduction* motor is fast becoming a vital factor in modern industrial applications.

RECOVERING PULP from waste paper for use in paperboard takes power. Driving the high inertia load imposed by the heavy rotating impeller within this Hydrapulper while meeting low starting kva restrictions is this 250-hp, 550-volt, 600-rpm, drip-proof wound-rotor induction motor.



Applying SYNCHRONOUS CONDENSERS

by H. H. ROTH
Motor and Generator Dept.
Allis-Chalmers Mfg. Co.

How synchronous condensers perform each of the three major functions for which they are applied is explained by the author.

SYNCHRONOUS CONDENSERS are used on present-day power systems for any one of the following purposes: (1) power-factor correction; (2) voltage regulation of transmission lines; (3) reduction of light flicker caused by electric arc furnaces. A synchronous condenser is essentially a synchronous motor running without mechanical load, and connected to an electrical system as a source of reactive kva.

Although reactive kva for power-factor correction can be furnished to a system by either synchronous condensers or static capacitors, only the synchronous condenser provides a variable output that is completely stepless. Switching of very small banks is necessary to even approach comparable fineness of control with capacitors. In addition, synchronous condensers may be operated at either leading or lagging power factor as required by system conditions, while capacitors operate only at leading power factor.

How they work

The operation of a synchronous condenser is perhaps best understood if considered as a generator operating in parallel with another generator. When two generators under manual voltage control are connected to a common bus and operated at no load, no current will flow between them if the excitation of both machines is properly adjusted.

However, if the field current of one generator is either increased or decreased, a circulating current will flow between them. If the field current of one machine is raised, the bus voltage will be increased, since the overexcited machine will furnish additional excitation to the second generator. Similarly, if the field current of one generator is decreased, the bus voltage will decrease and the underexcited generator will obtain a part of its excitation from the other machine. This interchange of excitation between generators, in the form of reactive kva (kvar) circulating between the machines, occurs on all systems.

Excitation for induction motors on any system must be obtained from the synchronous generator that supplies the kilowatts to drive them. The excitation taken by induction motors reduces the excitation of the generator in the same manner as an underexcited generator. Additional excitation must be supplied to the generator to compensate for the excitation required by induction motors or a drop in system voltage will occur.

A synchronous motor has its own source of excitation, and when supplied with a field current greater than that required for unity power-factor operation, its surplus excitation increases system excitation. This increased system excitation, resulting from the interchange of excitation between machines, will result in increased system voltage unless generator excitation is reduced. The interchange of excitation between machines permits a synchronous machine, such as a condenser, to obtain all or a part of its excitation from other machines on the same system, or to furnish excitation to other machines.

Synchronous condensers are a source of kvars

The generator with variable excitation described in the preceding example may be replaced with a synchronous condenser. In this case, the condenser may be considered as a generator without a prime mover. Normal generators are required to furnish both kilowatts (kw) and reactive kva (kvar) to the system, as dictated by the system load requirements. A condenser, since it has no prime mover, can supply only reactive kva.

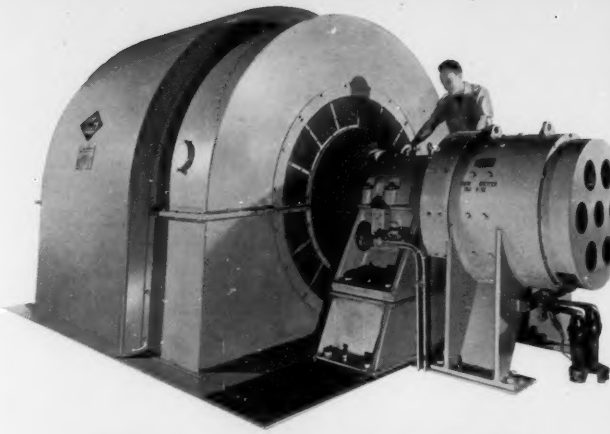
The basic operation of a condenser is shown in Figure 1. With the condenser connected to a system, its excitation may be varied until at some point its stator current reaches a minimum value, as shown by the low point of the curve. At this point the condenser is operating at unity power factor and is drawing from the system only sufficient in-phase current to meet its no-load losses.

If the condenser field current is then increased, its stator current increases because the condenser will then operate at some power factor other than unity. Considered as a motor, this machine is now drawing leading kvar from the system, and its operation is similar to that of an overexcited synchronous motor.

If the field current is lowered to some point below the unity power-factor point, the line current again starts to increase as the field current decreases. The condenser will then draw lagging kvar from the system, just as an induction motor would.

The use of such terms as "leading operation," "lagging operation," and "leading" or "lagging" kva may lead to considerable confusion when considering the operation of a condenser.[1] It is simpler to consider a condenser as being either overexcited or underexcited.

[1] "Speaking of Power Factors," R. A. Gerg, 4th Quarter, 1955 Allis-Chalmers *Electrical Review.*



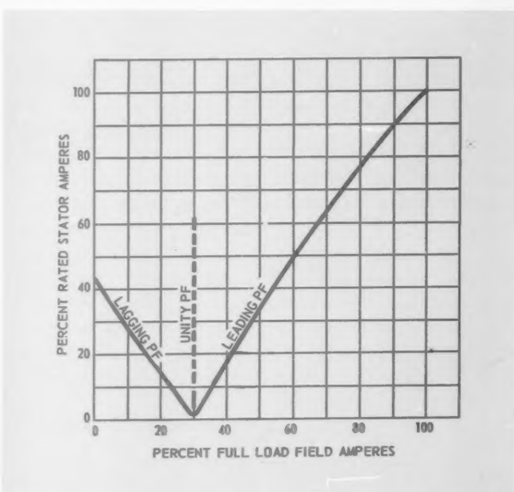
INSTALLED in a large industry plant having a preponderance of induction drive motors, this 25,000-kva synchronous condenser is used for power-factor correction. **(FIGURE 2)**

For power-factor correction

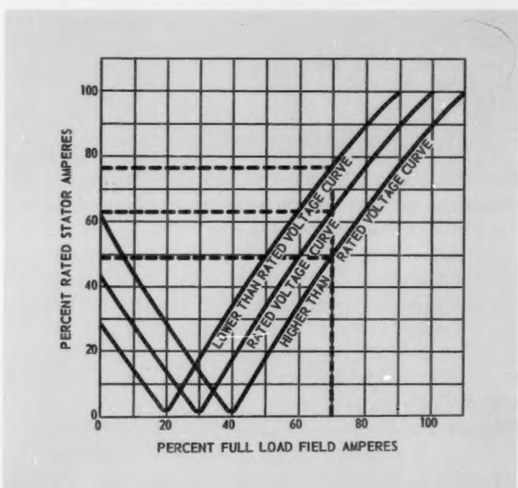
When a condenser is *overexcited,* its field current is greater than the value required for unity power-factor operation. This condition is commonly referred to as leading power-factor operation. Actually the condenser is furnishing *lagging* kvar required by inductive loads on the system . . . or, if considered as a motor, it is drawing leading kvar from the system. A power-factor meter would indicate that the condenser is operating at a leading power factor under this condition.

When *underexcited,* operating with field current less than that required for unity power-factor operation, the condenser is furnishing *leading* kvar to the system. If considered as a motor, the *underexcited* condenser is drawing lagging kvar from the other synchronous machines on the system, just as an induction motor would do.

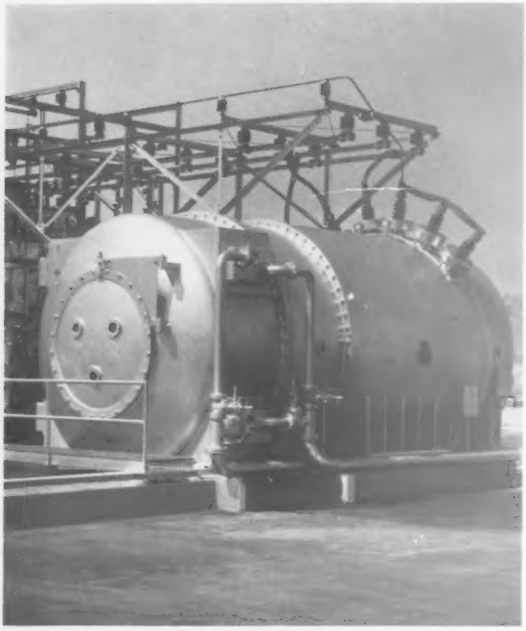
The electrical loads of most large power users are inductive in character because of the widespread use of in-



SYNCHRONOUS CONDENSER field current can be varied to supply either leading or lagging kvar to the connected system. When operated at leading power factor, synchronous condensers balance the lagging power factor of system inductive loads. **(FIGURE 1)**



WITH A DROP in system voltage, a synchronous condenser having fixed excitation draws an increasing amount of leading current. This increases the effective excitation of generators on the system and helps to stabilize system voltage. **(FIGURE 3)**



APPLIED TO UTILITY lines, this synchronous condenser, rated 48,000 kva at 15 psig hydrogen, performs the dual functions of correcting power factor and stabilizing voltage. **(FIGURE 4)**

duction motors and other electrical equipment operating at lagging power factor. While synchronous drive motors are helpful in improving the power factor of industrial loads,[2] induction motors are much more widely used because of their lower initial cost, particularly in the smaller ratings.

The application of synchronous condensers for power-factor correction often lies in the field of large industrial plants. Improvement in power factor by the installation of a condenser may be economical in order to obtain a lower power rate from the utility company. In applications of this type, a condenser will operate overexcited practically all of the time, and the underexcited capacity of the machine is of no value. An industrial application for power factor correction is shown in Figure 2.

For transmission line voltage regulation

When used in conjunction with long transmission lines, the problem is somewhat different. Condensers are usually installed near the load centers served by transmission lines to maintain desired voltage levels at the distribution point. In these applications, condensers may be required to alternately boost and buck voltage as load varies over a daily cycle.

When operating underexcited, a synchronous condenser draws a lagging current through the transmission line inductance and lowers system voltage. When overexcited it will raise system voltage. In this manner, transmission line voltage is regulated by varying the power factor at which the line operates.

[2] "Applying Motors to Balance Leading and Lagging Power Factors," E. N. Gigot, 2nd Quarter, 1956 Allis-Chalmers *Electrical Review*.

Synchronous condensers applied to transmission lines also assist in stabilizing line voltage during periods of system disturbances. The curves of Figure 3 indicate the condenser characteristics that make this possible. In the event of a system fault, the line voltage drops immediately. Assume that a condenser is connected to a system and is operating with 70 percent of rated field current. At the instant a fault occurs and voltage decreases, the condenser will immediately draw an increasingly larger current from the system without any change in its field current. This increase in leading current serves to increase the effective excitation of the generators on the system, thereby maintaining system voltage at a higher level than would be the case if the condenser were not in service.

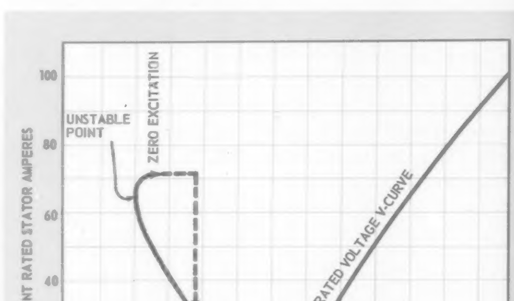
In a similar manner, if the line voltage should suddenly increase, the condenser will operate to assist in reducing system voltage. In this instance, the action of synchronous condensers differs from that of static capacitors. Static capacitors draw less current as voltage drops, more current as voltage rises and therefore do not provide a similar corrective effect. A synchronous condenser applied to utility lines for voltage regulation is shown in Figure 4.

Cooling affects characteristics

While condensers provide a useful function on power systems, they also consume kilowatts. It is therefore important to build condensers with losses as low as are consistent with good design.

Almost without exception, earlier condensers were air-cooled machines. However, most large condensers built today are hydrogen cooled in order to take advantage of the lower windage losses and better heat transfer provided by hydrogen. A 50,000-kva air-cooled condenser will have a full-load loss of about 860 kw, while a hydrogen-cooled machine of the same rating will have a full-load loss of about 740 kw.

There are some differences in the characteristics of hydrogen-cooled as compared to air-cooled condensers. Standard air-cooled machines have an underexcited capac-



UNDEREXCITED CAPACITY of a synchronous condenser, utilized for transmission line regulation during periods of light load, can be increased by negative excitation. **(FIGURE 5)**

ity of 50 percent rated overexcited capacity. The overexcited capacity of a condenser is determined by thermal considerations, while the underexcited capacity is determined by electrical design without any thermal considerations. When operated in hydrogen at ½ psig pressure, a given air-cooled machine can have its overexcited capacity increased 20 percent because of the better heat transfer characteristics. However, the underexcited capacity is not affected by the type of cooling used. Consequently, on hydrogen-cooled machines the underexcited capacity is only 42 percent of the ½ psig hydrogen-cooled overexcited rating.

The lagging, or underexcited, capacity of a condenser is the kvar that can be carried without the condenser becoming completely self-excited. In other words, the rated lagging capacity must be obtained without reducing the field current completely to zero.

Negative excitation increases capacity

When condensers are used for transmission line regulation, the underexcited capacity may be important, since at periods of light load the condenser may have to buck or tend to reduce the line voltage. Greater than normal lagging capacity can be built into a condenser, but this requires physically larger machines with resulting higher first cost. Within limits, greater than normal underexcited capacity can be obtained by using negative or reversed excitation.

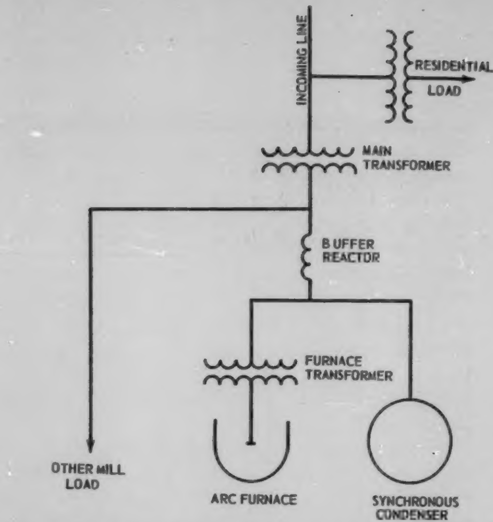
Operation of a condenser with negative excitation is shown in Figure 5. If the excitation current of a condenser is reduced to zero, the polarity of the excitation source reversed, and the field current again increased, the excitation becomes reversed or negative with respect to normal operation. An increase in the field current in the reversed direction causes the condenser to draw increased lagging kva from the system. There is, however, a limit to the amount of additional lagging capacity that can be obtained in this manner, since a point of instability will be reached at which the condenser will slip one pole and revert to positive excitation, as shown by the dotted line on the curve. Also, even when operating below the point of instability, a system disturbance may cause the condenser to slip a pole. The slippage of a pole is not a serious matter. Since negative excitation is used only during periods of light system loading, slipping a pole will merely cause a current surge of short duration which is hardly noticeable on a large system.

The amount of additional lagging capacity obtainable with negative excitation is variable and depends upon the design proportions of each particular machine. The voltage-regulating equipment used with condensers can be designed to provide for the use of negative excitation within the stability limits of each machine.

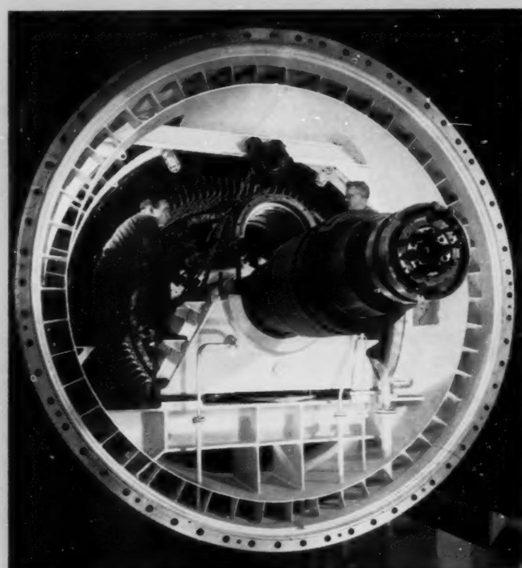
Arc-furnace applications

The use of large electric arc furnaces has grown rapidly in recent years. In many cases arc-furnace loads are served by transmission lines which also provide service to residential loads. This may introduce a problem of voltage fluctuations on the residential lighting load.

During the initial portion of an arc-furnace melting



VOLTAGE FLUCTUATIONS to residential loads resulting from an arc-furnace load are alleviated by paralleling a synchronous condenser with the arc furnace and supplying both through a buffer reactor. **(FIG. 6)**



TYPICAL of the special handling equipment supplied with hydrogen-cooled synchronous condensers for outdoor installations is this built-in chain hoist. **(FIGURE 7)**

AIR-COOLED synchronous condensers do not have weatherproof enclosures and require special housings when installed outdoors. **(FIG. 8)**

cycle, kva fluctuates widely. As the charge starts to melt, there are numerous cave-ins of unmelted portions of the charge which cause brief short-circuiting of the electrodes. The electrodes are automatically raised and lowered as the melting of the charge progresses, but movement is much too slow to prevent large fluctuations in kva demand. These fluctuations in turn cause voltage variations on the feeders serving residential loads from the same power line.

Under such conditions, feeder voltage regulators are of no value in maintaining uniform voltage on residential feeders. They require several seconds to operate, while the voltage fluctuations caused by arc furnaces are instantaneous in nature.

In the past, the chief objection to voltage variation caused by arc-furnace loads was the flicker introduced into residential lighting. During the initial melting portion of the arc-furnace cycle, light flicker may be very noticeable. More recently, with the advent of television, the problem has become more critical. Voltage variations cause noticeable contractions and expansions in television pictures and, if of sufficient magnitude, may cause the picture to "flop over," possibly several times per minute.

Synchronous condensers can be used to alleviate this condition.[3] A circuit diagram for an installation of this type is shown in Figure 6. A condenser is connected in parallel with the arc furnace and a reactor is installed between the load and the power line.

When a "cave-in" occurs in the furnace, it will usually short-circuit two electrodes, giving a high resistance single-phase short circuit; but in some cases it may short-circuit all three electrodes. The kva fluctuations set up by these short circuits are at a lower power factor than the kva demand for normal operation of the furnace. By using a condenser and reactor having the proper characteristics, variations in kvar can be corrected by the condenser, and eliminated from utility lines serving the steel mill load.

Synchronous condensers used for this application are usually somewhat special in nature, since they must have a relatively low reactance. No voltage regulator and its associated excitation system can operate fast enough to follow the voltage changes set up by arc furnaces. It is therefore necessary to depend on the inherent ability of the condenser to draw more or less kva instantaneously, as shown by Figure 3. In order to further assist in the corrective effect, condensers for this type of application are built with reactances considerably lower than normal. A low reactance condenser will have a greater change in its kvar load with a given change in voltage than will a condenser of normal reactance.

For arc-furnace applications, a condenser's transient reactance is usually considered as the measure of its effectiveness. A transient reactance as low as 30 percent may be specified. In comparison, a standard 50,000-kva condenser has a normal transient reactance of 58 percent for a hydrogen-cooled machine, or 48 percent for an air-cooled machine. In order to provide this lower reactance, it is necessary to utilize a physically larger machine, with a resulting higher initial cost.

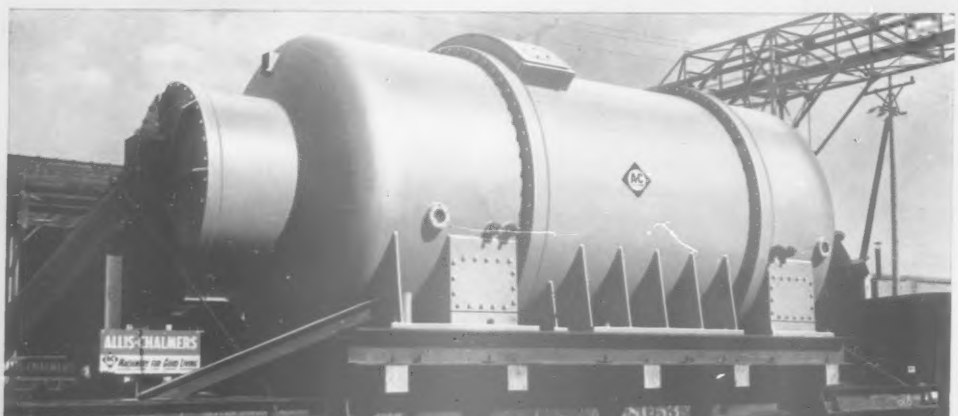
Condensers for arc-furnace applications are provided with voltage-regulating equipment similar to that used with a generator. In actual operation, excitation is set so that the condenser normally provides sufficient kvar to bring the arc-furnace load to about unity power factor. As kvar fluctuations are set up by the furnace, these transient kvar swings find a low reactance path to the condenser and, because of the presence of the buffer reactor, also find a high reactance path to the transmission line. Thus, the swings in kvar are absorbed by the condenser within its capability, and only kw load swings are carried by the power line. This effectively reduces the voltage dips on residential loads served from the same transmission line to a point where they are not objectionable.

Selection of a condenser for a given arc-furnace installation usually requires a calculating board study. In this way, effects of kva capacity and condenser reactance on overall voltage stability can be accurately determined for the particular system involved.

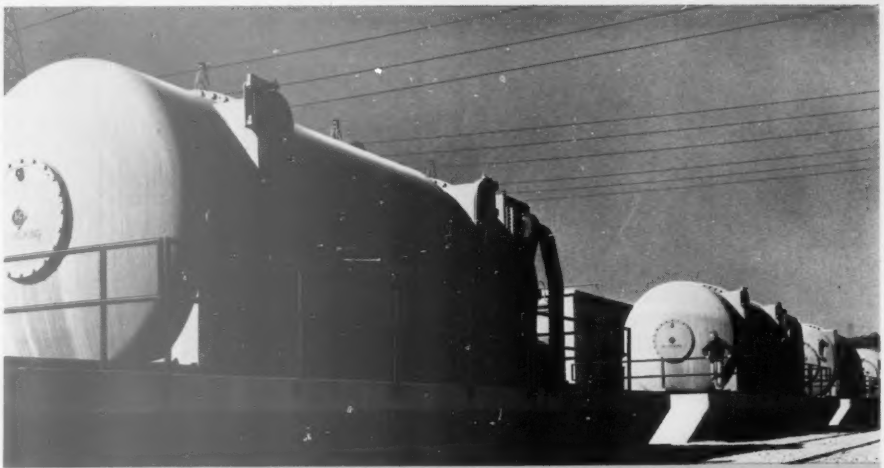
Hydrogen-cooled units are weather protected

Hydrogen-cooled condensers are inherently suitable for outdoor installation because of their gas-tight enclosures.

[3] "Synchronous Condenser at Arc Furnace Load Steadies Power Demands," S. E. McDowell, 4th Quarter, 1954 Allis-Chalmers *Electrical Review*.



THIS 50,000-kva synchronous condenser is being shipped completely assembled to simply installation. (FIGURE 9)



SYNCHRONOUS CONDENSERS for power-factor correction may be required on large industrial loads such as imposed by this Atomic Energy Commission plant. (FIG. 10)

However, outdoor installations are usually in substations where no large crane is available. Consequently these machines are provided with special handling equipment to facilitate field assembly.

This same handling equipment is also used during inspection and overhaul procedures. Built-in handling equipment used for bearing cap removal is shown in Figure 7.

Air-cooled condensers are not in themselves suited for outdoor installation, but require a weather-proof housing. A typical installation of outdoor air-cooled condensers is shown in Figure 8.

Hydrogen-cooled condensers require a source of cooling water in order to remove the heat losses from the machine. Air-cooled condensers may be arranged with closed-circuit cooling systems, which also require cooling water. However, if water is not available, or would be very expensive to provide, air-cooled condensers can be self-cooled. Self-cooled machines are designed to draw in outside ambient air which is circulated through the machine, then discharged to atmosphere.

It is becoming a common practice to ship synchronous condensers completely assembled whenever possible. While this has the desirable effect of reducing installation time, it of course requires the use of a special freight car, and a careful check of the proposed routing in order to determine if sufficient clearances are available on the railway lines. While these restrictions impose limits in both physical size and weight, hydrogen-cooled condensers as large as 50,000 kva have been shipped completely assembled except for such items as terminal bushings. Shipping in this manner simplifies erection at the destination. A completely assembled 50,000-kva condenser, ready for shipment, is shown in Figure 9.

Control an important part of installation

Since most condensers must operate with varying kvar load requirements, some method of automatic excitation control is necessary. This control may operate either on the basis of maintaining a constant voltage or a constant power factor.

For either application the excitation control equipment is essentially the same. For control on the basis of voltage, a voltage regulator identical to that for a synchronous generator is used. One additional feature is used for condenser application. The regulator is provided with a current-limiting feature which prevents overloading the condenser when the corrective capacity required by the system is beyond the condenser's capability. When this condition occurs, the current-limiting feature causes the regulator to operate on the basis of current rather than voltage.

These regulators may also be arranged to regulate on the basis of power factor rather than voltage. This requires some modification of the regulator circuit, but the regulator equipment is essentially the same in either case.

When a need exists for power-factor correction or voltage regulation on transmission lines, both capacitors and synchronous condensers are usually considered for application to the system, since reactive kva may be furnished by either. A comparison of operating characteristics for condensers and capacitors points up several advantages for synchronous condensers.

For example, a condenser may be operated at either leading or lagging power factor as required by system conditions. Capacitors operate only at leading power factor. A condenser provides stepless variations of kvar within the limits of its rating, while switching of capacitors in very small banks is necessary to even approach comparable fineness of control.

Although condensers cost more than static capacitors and have higher losses, they have substantial overload capacities, while capacitors have none. In addition, synchronous condensers have a stabilizing effect on a system under sudden load changes, both because of their electrical characteristics and because of their mechanical inertia.

Designing SWITCHGEAR "BUS RUNS" TO STAY COOL

SUBSTATION arrangement with overhead bus runs connecting 13.8-kv switchgear groups has provision for triple ending to gain additional transformer capacity.

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Switchgear bus run temperatures are limited to protect insulation of both buses and equipment to which they are connected.

SWITCHGEAR BUS RUNS generally consist of metal-enclosed buses that are used to connect power transformers, motors, or generators to switchgear units or groups. Some bus runs carry currents of 6000 amperes or higher. However, they must be so designed that they do not transmit heat into the equipment to which they are connected. Although some heat may be generated by eddy-current loss in the bus housing, the temperature rise in bus runs is for the most part the result of heat generated in the conductors themselves. Generally, bus runs are designed either with adequate spacing between the buses and their housing or with nonmagnetic housings to minimize eddy-current and hysteresis losses.

In bus runs, as in other electrical devices, there is a limit to the permissible temperature rise. Usually this limit is set by the maximum safe temperature which the conductor insulation can stand continually without deterioration. This maximum temperature may also be limited by other considerations such as avoidance of "heat-pumping" to other equipment to which the bus connects and whose temperature rise limits may be lower. For Class A insulation NEMA Standards allow a maximum conductor temperature rise of 50 C over an outside ambient of 40 C, or a maximum conductor temperature of 90 C for continuous operation.

As soon as the bus run is energized, the temperatures of the bus and the housing begin to rise exponentially. For a constant current and constant ambient conditions, the temperature reaches a leveling off value within a few hours. This value, the ultimate temperature, is reached when there is a balance between the heat developed by the bus and the heat lost. To be able to calculate the bus I^2R losses accurately, it is important to analyze the methods of heat transfer from the conductors.

Ac bus heating calculations are complex

With direct current, the calculation of resistance losses in the copper bus bars is simple because the current density is uniform. Given the cross-section area of the bus, one can calculate its resistance and obtain the watts loss by multiplying the resistance by the square of the current.

With alternating current, however, the problem becomes involved because of several factors, most important of which are the "skin effect" and "proximity effect." Both these effects are caused by the flux variation which takes place around a conductor carrying alternating current, and both affect the watts loss in the conductor through their effect on the uniformity of the current density in the conductor.

Skin effect refers to the crowding of the current toward the conductor surfaces. It is caused by the non-uniform flux distribution in the cross-section area of the conductor and results from higher self-inductance in the center of the conductor. The higher the frequency, the greater the skin effect.

The proximity effect refers to the crowding of current to the side of the bus cross section and is caused by the nonuniform flux distribution resulting from the mutual inductance of parallel conductors. With the parallel bus

carrying current in the same direction, the current density becomes high on adjacent sides of the bus. With current flow in the bus in the opposite direction, the current density on the far sides of the bus becomes high. Again, the higher the frequency, the more pronounced the proximity effect.

Proximity effect is small

It has been shown experimentally[1] that at frequencies below 100 cycles per second the proximity effect is relatively small, and for many 60-cycle switchgear buses the proximity effect is less than 2 percent. For this reason, the entire current-distortion effect may be broadly referred to as "skin effect."

The skin-effect resistance of a conductor composed of a few rectangular bars, arranged in parallel planes and slightly spaced from each other, can be closely approximated. Figure 1 is a curve for solid wire taken from a family of curves.[2] In a later paper by H. B. Dwight, G. W. Andrew and T. W. Tileston, Jr., of Massachusetts Institute of Technology, it was shown that this curve compares closely to the characteristics of flat bus-bar arrangement, provided the number of bars used per conductor does not exceed four.

The value of the dc resistance of the conductor can be obtained from various published data. Usually the resistance given in such data is the resistance at 20 C. From this value, the resistance of the copper conductor at the working temperature can be obtained from the following formula:

$$R_t = \frac{R_o}{\dfrac{235 + t_o}{235 + t_o + t_d}}$$

where R_t = the dc resistance at the working temperature —70 C, 80 C, or 90 C—depending on the permissible temperature rise over outside ambient.

R_o = the dc resistance at t_o temperature.

t_o = the temperature at which resistance is given (usually 20 C).

t_d = the difference between the working temperature and "t_o".

For aluminum conductor the same formula is used except that 220 is substituted for 235. Having thus determined the dc resistance R_t of the conductor per 1000 ft, one can calculate the value $\sqrt{\dfrac{f}{Rdc}}$ and then, referring to the curve, can find the value of skin-effect ratio $\dfrac{Rac}{Rdc}$. From this ratio he can calculate the alternating-current resistance of the conductor and the I^2R losses.

After the conductor losses are determined, then the most effective methods of dissipating these losses are studied and applied.

From basic physics we know that heat is transferred from hot bodies to surrounding media by radiation, convection and conduction. The heat lost by conduction in a body of uniform section is directly proportional to the cross-section area and the temperature gradient from the hot section area to the cold section area. It is inversely proportional to the thermal resistivity of the material and the distance (length or thickness) from the hot section area to the cold section area. Hence, the heat lost by conduction in bus runs is usually very small and can be neglected.

The most effective way of transferring heat from a switchgear bus is by convection. In order to get the maximum conductor cooling by convection, switchgear engineers try to arrange buses and bus housings so that the movement of air both inside and outside the housing has minimum resistance.

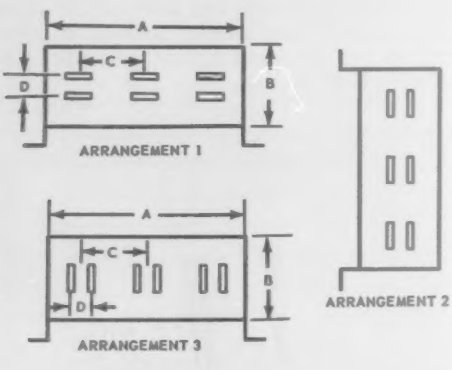
The transfer of heat by radiation is also important to switchgear engineers. The transfer of heat by radiation is expressed by the Stefan-Boltzmann law, which states that the heat radiated is proportional to the emissivity factor times the difference of the absolute temperature across a medium. The emissivity factor can vary from approximately 0.1 for clean, nontarnished metal surfaces to 0.95 for dull dark-painted surfaces.

It is difficult to derive formulas for calculating temperature rises of switchgear buses, since complicated mathematical manipulations are required to determine the transfer of heat by conduction, convection, and radiation. For this reason bus designers resort to empirical data found in publications or other data derived experimentally. Theoretical study of heat transfer, however, is valuable in evaluating test results and developing empirical equations and empirical constants.

CURVE is used to approximate increase in resistance resulting from skin effect in some laminated bus designs. **(FIG. 1)**

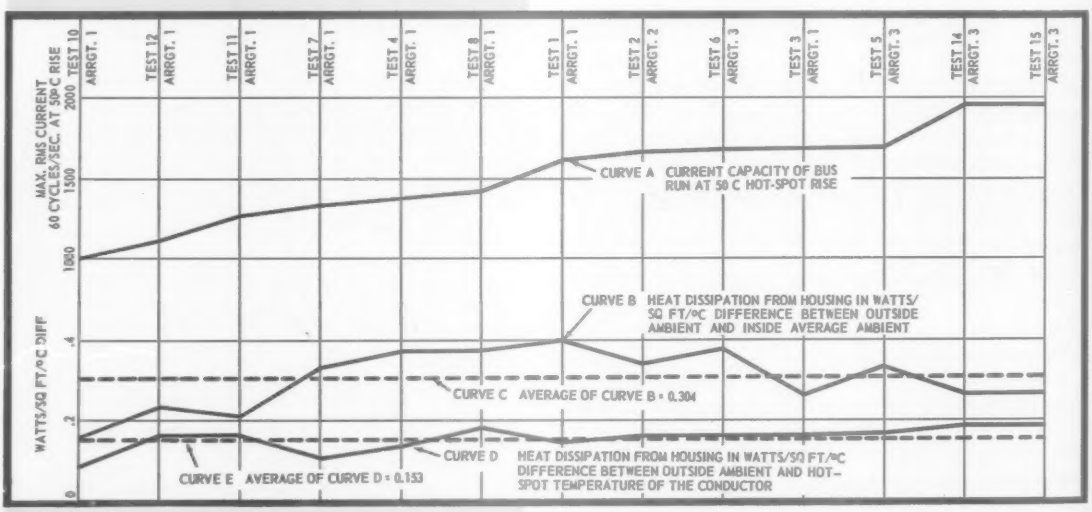
TABLE I

Test No.	Number and Size of Bars Per Phase, Material and Bar Spacing	Plane and Phase Center Spacing	Housing Dimensions, Plane Position and Inside Paint Color	Bus Surface Treatment or Covering	Amps for Hot-Spot Rise of 50C
1	Two ½"x3" Cu—½"	Horiz.—7"	10⅝"x23⅝" Horiz. Grey	⅛" Insul. Tube	1620
2	Two ½"x3" Cu—½"	Vert.—7"	10⅝"23⅝" Vert. Grey	⅛" Insul. Tube	1675
3	Two ½"x3" Cu—3"	Horiz.—7"	10⅝"x23⅝" Horiz. Grey	⅛" Insul. Tube	1690
4	Two ½"x3" Al—½"	Horiz.—7"	10⅝"x23⅝" Horiz. Grey	⅛" Insul. Tube	1380
5	Two ½"x3" Cu—½"	Vert.—7"	10⅝"x23⅝" Horiz. Grey	⅛" Insul. Tube	1700
6	Two ½"x3" Cu—2"	Vert.—7"	10⅝"x23⅝" Horiz. Grey	⅛" Insul. Tube	1685
7	Two ½"x3" Cu—½"	Horiz.—7"	10⅝"x23⅝" Horiz. Grey	Bare—Natural	1340
8	Two ¼"x3" Cu—1"	Horiz.—7"	10⅝"x23⅝" Horiz. Grey	⅛" Insul. Tube	1430
10	Two ½"x3" Cu—1"	Horiz.—4"	6¼"x13⅝" Horiz. Grey	Bare—Natural	1000
11	Two ½"x3" Cu—1"	Horiz.—4"	6¼"x13⅝" Horiz. Black	Painted Black	1270
12	Two ½"x3" Al—1"	Horiz.—4"	6¼"x13⅝" Horiz. Black	Painted Black	1110
14	Two ½"x4" Cu—½"	Vert.—7"	10⅝"x23⅝" Horiz. Grey	Painted Black	1960
15	Two ½"x4" Cu—½"	Vert.—7"	10⅝"x23⅝" Horiz. Grey	⅛" Insul. Tube	1960



Empirical data obtained

To obtain design data and to check experimentally the current ratings that could be safely and economically established, tests shown in Table I and Figure 2 were conducted with nonsegregated bus runs,[3] such as shown in Figure 3, to supplement data found in publications. These tests were run with various conductor cross-section areas and geometrical configurations. Each housing consisted of a ¼-in. thick steel channel-formed base and 1/16-in. thick steel channel-formed cover. Each bus run consisted of two sections, joined to make the overall length of the bus run equal to about 12 feet. Copper bus bars were used in most tests, but on a few other tests aluminum bus bars were substituted to obtain relative data.



USEFUL DATA provided by test curve and curves developed empirically provide basis for design of switchgear bus runs. **(FIGURE 2)**

METAL-ENCLOSED BUS DESIGN for 600-volt runs involves heat dissipation problems like those of high voltage designs. The bus shown is rated 600 volts, 3000 amperes. **(FIG. 3)**

In each test, the current in the three phases was equalized and adjusted to a value which produced a hot-spot temperature rise of 50 C over outside ambient on at least one conductor after the temperature leveled off. The duration of each test varied between 5½ to 6 hours.

Data analyzed

An analysis of the test results listed on Table I shows the following:

1. Tests 1 and 2 show that changing the housing from a horizontal plane arrangement to a vertical plane increased the current-carrying capacity of the bus run by about 3.5 percent.

2. Tests 1 and 3 show that, for a horizontal arrangement of bar and housing, increasing the space between bars of the same phase from ½ in. to 3 in. increased the current-carrying capacity of the bus run by about 4.3 percent.

3. Tests 1 and 4 show that, in a horizontal arrangement of bars and housing, changing the conductor material from copper to aluminum reduced the current-carrying capacity of the bus run by about 17 percent.

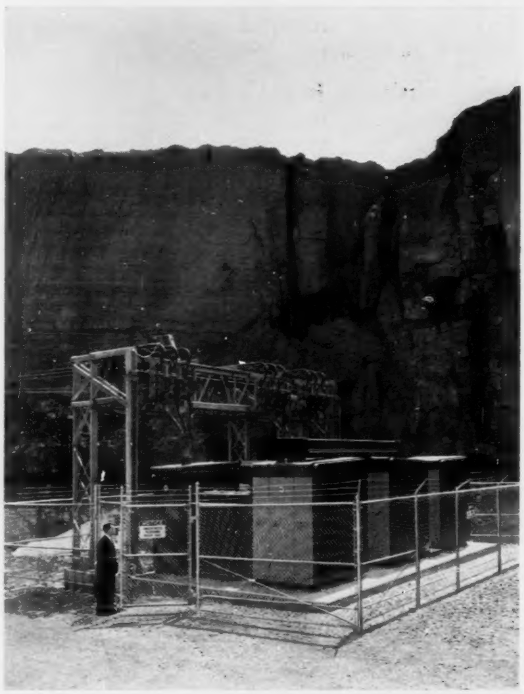
4. Tests 1 and 5 show that changing the bars from a horizontal plane arrangement to a vertical plane arrangement increased the current-carrying capacity of the bus run by about 5 percent.

5. Tests 5 and 6 show that, with bars arranged in a vertical plane, changing the bar spacing in each phase from ½ in. to 2 in. had very little effect on the current-carrying capacity of the bus run.

6. Tests 1 and 7 show that, in a bus run having a horizontal bar arrangement, copper bars insulated with ⅛-in. thick phenolic tubes carried about 21 percent more current than bare copper bars of equal section. These results agree with earlier published information.[4] For a similar bar arrangement, Tests 4 and 7 show that aluminum bars insulated with phenolic tubes carried a current slightly larger than bare copper bus bars of equal section.

7. Tests 7 and 8 show that, in a horizontal bar arrangement, a bus run equipped with two copper bars ¼ in. by 3 in. per phase, each insulated with ⅛-in. thick black phenolic tubing, had a current-carrying capacity 7 percent higher than a similar bus run equipped with bare copper bars of twice the cross-section area.

8. Tests 3 and 8 show that doubling the thickness of copper bars increased the current capacity of the bus run by only 18 percent, even though the thicker bars were spaced wider apart.



LOW VOLTAGE SWITCHGEAR units for 480-volt circuits supplying a quarry have overhead bus connecting two of the units, thus making a double-ended arrangement. The third unit operates as a single-ended unit on the 2400-volt system. **(FIG. 4)**

9. Tests 7 and 10 show that, in a horizontal bar arrangement, changing the size of housing from 10⅝ in. by 23⅝ in. to 6¼ in. by 13⅝ in. decreased the current-carrying capacity of the bus run by 34 percent, even though the bars were spaced ½ in. farther apart in the smaller housing.

10. Tests 10 and 11 show that, in a horizontal bar arrangement, painting the copper bars and the inside of the housing dull black increased the current-carrying capacity of the bus run by 27 percent over that equipped with bare copper bars, confirming published information.[4]

11. Tests 11 and 12 show that, in a horizontal bar arrangement, with the bars and the inside of the housings painted dull black, the bus run equipped with aluminum bars carried about 14 percent less than the one equipped with copper bars. The reduction in this case is slightly less than that shown by analysis 3.

12. Tests 14 and 15 show that, in a bus run with vertical bar arrangement, copper bars insulated with ⅛-in. thick black phenolic tubing carried as much current as dull black painted copper bars. Evidently, then, the optimum increase in current-carrying capacity obtainable by insulation is reached when the conductor is insulated with ⅛-in. thick black phenolic. Tube thicknesses larger than ⅛ in. cause a decrease in current-carrying capacity, and similar tests conducted by others have shown that a copper conductor insulated with ¼-in. thick insulating tube has the same current-carrying capacity as a bare copper conductor of equal cross section. Insulation thicknesses larger than ¼ in. reduce the carrying capacity to below that of the bare conductors.

Energy dissipated in bus runs

The current-carrying capacity values for bus runs obtained in these tests for a 50 C hot-spot temperature rise are plotted as Curve *A* in Figure 2. These values are plotted in the order of current ascendancy, or increase, rather than in the order of test numbers as appears in Table I.

The watts energy loss per foot length of bus run was calculated for each test by using these values of current and the *Rac* values of the conductor resistances. From these watt values, and from the outside surface area per foot length of bus run of each housing, the watts per square foot per degree centigrade rise above outside ambient were calculated and plotted in Curves *B* and *D* of Figure 2. Curve *B* shows the watts/sq ft/°C rise from outside ambient to the average inside ambient temperature, and Curve D shows watts/sq ft/°C rise from outside ambient to the conductor hot-spot temperature. The average of values in Curve *B* was found to be equal to 0.304 watts/sq ft/°C and is drawn as Curve *C*. Also, the average of values of Curve *D* was found to be equal to 0.153 watts/sq ft/°C and is drawn as Curve *E* on Figure 2. From Figure 2, a design engineer can see at a glance the results obtained from these tests and apply the data given there to other similar designs.

Actually, in bus runs similar to those used on these tests, the housing surface area has to dissipate some eddy-current and hysteresis losses in addition to the I^2R losses in the conductors. However, no effort was made in the tests to determine these losses.

REFERENCES

1. "Experimental Researches in Skin Effect in Conductors," A. E. Kennelly, F. A. Laws, and P. K. Pierce, AIEE *Transactions*, Vol. 34, 1915, pp. 1953—2018.
2. "Skin Effect and Proximity Effect in Tubular Conductors," H. B. Dwight, AIEE *Transactions*, 1922, p. 189.
3. "Packaged Bus Protects Electrical Conductors," J. W. Timmerman, 1st Quarter, 1951, Allis-Chalmers *Electrical Review*.
4. "Copper for Bus Bars," Copper Development Association of London, Publication No. 22, 1936.